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CONTENTS

Mech. Eng. Sci. J. **26** (2), 39–98 (2007)

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A FEW PROOFS FOR NONEXISTENCE OF THE METASTABLE STATES

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Abstract: This paper is the bigger part of one until now unpublished author's work whose title is "A few proofs for nonexistence of the metastable states". Because of a big volume of the work, the problems of supersaturated (metastable) steam which appears at the flowing of slightly, superheated, saturated or wet steam in the convergent and Laval nozzles will be discussed in the main. This steam is mentioned in the literature as one between of the strongest proofs for existence of the metastable states in the substances. In this work the steam is not one-phase gaseous metastable steam, as it was thought until now, but that it is nonequilibrium wet steam in which during the expanding process in the nozzles extreme small particles condensate, consisted of two, three or only few agglomerated molecules are formed which stay in heat, mechanical and internal nonequilibrium with the rest of the expanding gaseous phase of the steam. It means, that this steam, which is called a supersaturated or metastable steam, in fact does not exist in reality because it is nothing else but only nonequilibrium wet steam consisted of two phases: the expanding gaseous phase of the steam in the nozzle and the mentioned small and nonequilibrium particles condensate which are formed there.

The new theoretical explanation presented in this work, gives possibility not only for a total physical comprehension of the essence of supersaturated steam, but gives possibility for evaluation of the properties of state of this steam in the end of supersaturation which happens at reaching the corresponding Wilson line in the *h,s*-diagram. The paper also explains the reasons due to which it comes to appearance of the sudden little pressure condensation rise which happens regularly in the Laval nozzles immediately after the end of supersaturation of the steam in them, respectively at once after reaching the Wilson line in the *h,s*-diagram and the manner of calculation of the properties of state of the steam in the end of the rise is also presented. After this rise, the steam goes on expanding in equilibrium forming bigger and equilibrium droplets condensate until the exit section of the Laval nozzles, and as such it is not interesting here for further observations.

In this paper will be discussed shortly and other examples for existence of metastable states in the substances, mentioned in the existing literature, as, for example, the case of cooling of water in little blinded glass ampoules which has been done by Berthold. This experiment also points out the possibility for achievement of negative absolute pressures in the substances, which is very unbelievable and impossible (??). As opposed to this example, the author of this work makes experiments by cooling clean saturated water from 1 bar situated in a bigger glass vessel and finds that in this case neither metastable states nor negative absolute pressure appear. In the literature there is an example of the metastable states existence and the case of heating droplets of water dived into oil (with the same density as water), which have not evaporated up to the temperature of 180°C, although the pressure (of the oil and droplets) has been approximately equal to the atmospheric pressure, etc.

Keywords: supersturated steam; metastable states; nonequilibrium wet steam; little nonequilibrium particles condensate; little pressure condensation rise; equilibrium droplets condensate

1. INTRODUCTION

The title itself of this work "A Few Proofs for Nonexistence of the Metastable States" shows that it deals with existence or nonexistence of the metastable states at the real substances. If we want to discuss these things we, at first, must see **what the metastable state is and how it is defined.**

The notion of the metastable state is introduced in Thermodynamics from a need to give any physical explanation for those parts of the Van der Waals subcritical isotherms which in the region of wet steam have a waved form, shown in Fig. 1. As far as these waves are concerned it could be said quite freely that they have not been confirmed up to now by any standard experiment, except the belief that something like that has been reached in any "special" conditions, as for example at the flow of supersaturated (and subcooled) steam through the nozzles, at the flow of superheated liquids through the nozzles, at heating droplets of water in oil with equal density as the water, at cooling (or heating) of water in little glass ampoules and in many other examples. For those states, which have been reached in those special conditions, as for example the state 3 in Fig. 1, it has been asserted that they lie on the waved parts of the Van der Waals isotherms with what in essence has been desirable to prove that those waved parts have totally physical meaning (although they cannot be reached with any standard experiment, as for example with an usual isothermal expansion or compression of any real substance). From that another very incredible conclusion followed (opposite to that which has been clearly seen from the usual experiments) that in any special conditions the passing from gaseous to liquid phase (and reverse) must proceed anyhow continuously, or more exactly, as it has followed from the Van der Waals equation. This very incredible and experimentally not proved conclusion has been confirmed by one, at first sight very firm mathematical proof, known under the name of Maxwell's principle. According to this principle the shaded areas under and over the experimental (straight) isotherms in the wet region (see Fig. 1) are mutually equivalent. It has followed that the waved Van der Waals isotherms and the corresponding real (straight) isotherms in the wet region (Fig. 1) in fact are mutually equivalent **equilibrium processes**. From that belief in the totally physical meaning of the Van der Waals equation and the Maxwell principle, a conclusion has followed that (these processes and) these states, which have been reached in the before mentioned special conditions, and which have been called the metastable states**,** in fact are **equilibrium states**, see Ref. [1], page139 and Ref. [9], page 96.

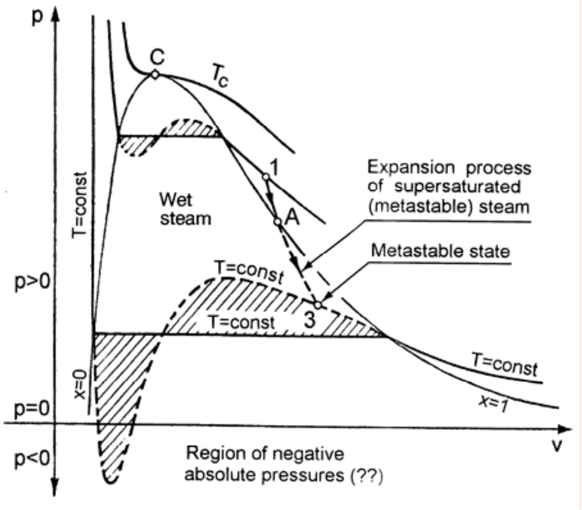


Fig. 1. Presentation of the straight (experimental) and the waved Van der Waals isotherms in the region of wet steam

2. NEW COMPREHENSIONS

However, in recent time one totally opposite, but more correct opinion for the character of metastable states, has begun to intrude that these states in essence are **nonequilibrium states** (see Ref. [2], page 24). This totally opposite comprehension for the notion and definition of the metastable states (in relation to the previous notion) has followed from the well known fact, on which whole classical thermodynamics is based, that one process can proceed in equilibrium if only it lasts sufficiently long, or more exactly, as long as it is possible to reach a total thermodynamics' equilibrium (simultaneous heat, mechanical and internal equilibrium) in every elementary part of the process. That time which is necessary for restitution of such equilibrium, at proceeding of any process, is called **relaxation time** (see Ref. [5], page 319). From this inexorable fact the conclusion has followed that only that process which lasts longer than it is its indispensable relaxation time could proceed in equilibrium and reversible (if the friction is eliminated), but in the opposite case it will be surely nonequilibrium and irreversible (regardless if the friction is eliminated or not).

This new and more correct comprehension for the nonequilibrium character of the metastable states has followed again from those same experiments which were done in special conditions, as for example, the flowing of supersaturated and subcooled steam in the nozzles and alike. From those experiments it has been seen that the expansion process in the nozzles has proceeded extremely quickly, which means at a shorter time's interval than the time necessary for reaching relaxation of the process and restitution of thermodynamics' equilibrium in the system, therefore the expansion in the nozzle has proceeded in nonequilibrium and with supersaturation of the steam. This conclusion has been in principle totally correct because as an experimentally palpable and measurable proof for the nonequilibrium character of the metastable processes (and states) it has been mentioned the **extreme velocity** of proceeding of the process and the **insufficient relaxation time**, but not the Van der Waals equation.

However, and besides this convincing conclusion for the nonequilibrium character of the metastable processes (and states), the contemporary authors have not abandoned completely the Van der Waals equation because it has served them (with help of the Helmholtz function for free energy, $f = u - Ts$) as an "additional" explanation of that which they have above already explained for the nonequilibrium character of the metastable states (on the basis of the insufficient relaxation time). But regretably, these "additional" explanations which are based on the Van der Waals equation (see Ref. [2], page 25) in principle are totally contradictory because they again lead toward the original conclusion for the **equilibrium character** of the metastable processes and states.

The tragedy of these contradictions to be still bigger is that all contemporary authors who have studied the process of supersaturated (metastable) steam have asserted for that process that it is an **nonequilibrium process** (on the basis of the previously explained fact for the insufficient relaxation time), but after that they have proclaimed the same process for an **isentropic process**, and have showed it in the *h,s* and *T,s*-diagram with a vertical straight line s = const. (see Ref. [2], page 137) which in no way goes together, because if it is asserted for a process that it is a nonequilibrium process, then for it in no one case could be asserted that it is also an isentropic process (??).

From what has been said up-to-now, the following conclusion could be drawn:

– first, that the metastable states are **equilibrium states**,

– second, that the metastable states are **nonequilibrium states**, and

– third, that the metastable states again are **equilibrium states** (??).

From these contradictory definitions nobody could conclude uniformly **whether these states after all are equilibrium or not** (??).

One very important example for these contradictions which are connected with the up-to-now notion and definition of the supersaturated (metastable) steam, could be mentioned and the case when the expansion process of **nonequilibrium supersaturated steam** A-3, Fig. 2, is compared with the corresponding expansion process of **equilibrium wet steam** A-2, at which as starting comparable state for both processes the state A which lies on the limit curve of saturation, x = 1, has been adopted and as final states are adopted (see Ref. [2], page 26) the corresponding states 3 and 2 which are reached at the same final pressure $p_3 = p_2$. At this consideration the first part of the process, respectively the process of superheated steam 1-A, is not interesting for discussion because it is equal in both cases.

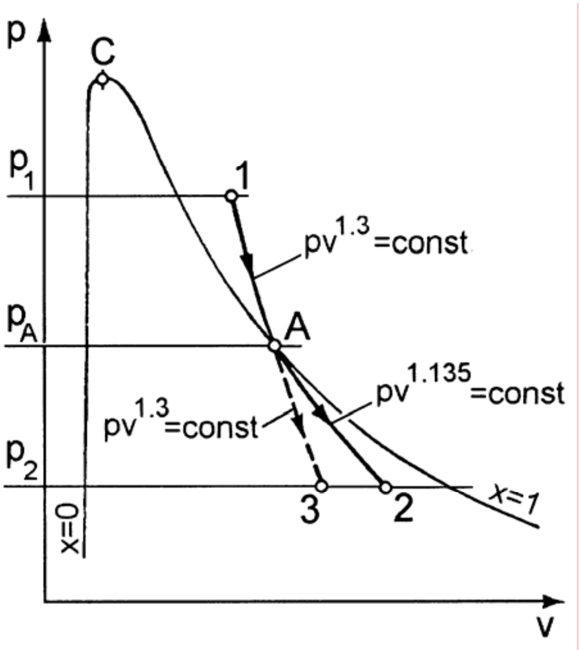


Fig. 2. Presentation of the processes 1-A-2 and 1-A-3 in *p,v*-diagram

The contemporary authors explain these two processes so that the process of nonequilibrium supersaturated steam A-3 (see Fig. 2) approximately shown with an **isentropic curve** (??) $pv^{k'}$ = const, whose exponent k' they adopt equally the isentropic exponent of the superheated steam $k = 1.3$, which also means as for the part of the process 1-A, but the corresponding process of equilibrium wet steam A-2 in the same region **also shown with an isentropic curve** pv^k = const, with that difference that for it steam the exponent k they adopt according to the empirical Zeüner relation (1840), $k = 1.035 + 0.1x$, which for the starting saturated steam, with $x = 1$, turns into $k = 1.135$. (Larger discussion for the numeric values of the exponents k' and k is given in the attachment 1.)

From such presentation a conclusion follows that in the wet region, beginning from the same starting-point A (Fig. 2) in different conditions, **two different isentropic processes** could proceed, with different exponents, $k' = 1.3$ and $k = 1.135$, which in this work is proved that it is absolutely incorrect. This incorrectness follows from the previously explained fact, according to which it cannot be said for one process that it is a nonequilibrium process and after that to be asserted that it is also an isentropic process (??). A conclusion has followed from it (this work) that in the region of wet steam **only one unique isentropic process (but not two) could exist** and that it process is the process of equilibrium wet steam which proceeds with the exponent $k = 1.135$. According to that, the process of supersaturated (metastable) steam could be everything but never an isentropic process, as it has been asserted up to now.

The inexactness of the up to now explanations to become still bigger, the same authors, who have compared the processes of supersaturated and equilibrium wet steam, have showed those two processes in the *p,v*-diagram with **different isentropic curves**, A-3 and A-2 (see Fig. 2) while in the *h,s*-diagram (see Ref. 2, pages 26 and 137) those two different processes they have showed with one same **common isentropic process** A-2 (see Fig. 3) which is also absolutely wrong. This unlogic and inexactness follows from the fact that the *p,v*, *h,s* and *T,s*-diagram are mutually equivalent diagrams, which means that everything which exists in one diagram must also exist in the other two diagrams. According to that, if the processes of supersaturated and equilibrium wet steam are showed in *p,v*-diagram with different curves A-3 and A-2, it means that in the *h,s* and *T,s*-diagram for these two processes there must also exist two different curves (as it will be shown in this work, but not to be shown only with one unique common isentropic process A-2, as it has been done up to now, see Fig. 3). This work in essence starts with disentangling of this Gordian knot that is shown on Figs. 2 and 3. The solution of this knot will be presented in the next chapters with all necessary details.

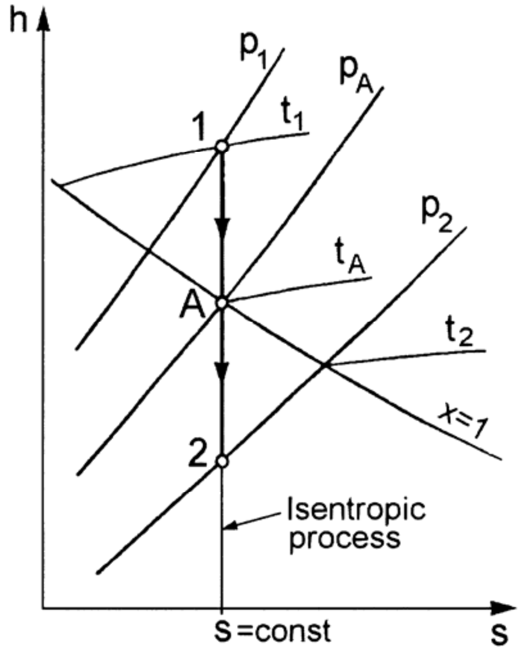


Fig. 3. Up to now manner of transferring of the processes 1-A-2 and 1-A-3 from *p,v* in *h,s*-diagram

Now the next question could be "How and why were these heavy errors in definition of the metastable states made"? The author's answer to these questions is the following:

1. These errors were made, first, because none of the up-to-now authors, who have studied the problem of the metastable states has not had courage to free totally from those "comprehensions" which have followed from the Van der Waals equation and the Maxwell principle, because every expressed unbelief in its (unproved) physical meaning in the region of wet steam would bring great trouble to every author.

2. The second error that has been made is that in the classical (equilibrium) thermodynamics such "notions", as for example, stable, unstable, labile or metastable state, have been introduced which "notions" the equilibrium thermodynamics simply said, does not recognize and "does not understand". It understands only two states, **equilibrium and nonequilibrium state, and no more** (what is similar to the computers which also understand only two states, "1" and "0", and no more). According to that, if we want to make use of the thermodynamics as a science, we, at first, all these "new introduced notions", stable, labile, metastable state, etc. must translate in thermodynamics language, which contains only two words which the thermodynamics understands, equilibrium and nonequilibrium state. If we do not do it we in essence leave the basic principles of equilibrium thermodynamics and therefore it is not odd that we are falling in such blind-alleys, as it is the case with the metastable states, which are introduced in thermodynamics only in order to be able to explain and prove the things which cannot be proved, i.e., that the Van der Waals subcritical isotherms in the region of wet steam have any physical meaning. This was wanted to be proved very persistently and in spite of the fact that hundreds standard experiments, with hundreds different substances, have showed that it is totally physically absurd.

3. The third error which has been made in this field, and which in essence has followed from the previous two, is that none of those authors, who have noticed the nonequilibrium character of the metastable (processes and) states, have asked themselves what is this which happens with the structure of substance when it is exhibited on one so extreme rapid process, as it is, for example, the expansion of supersaturated steam in the nozzles. All those authors have stayed deeply convinced that for the time of proceeding of those processes it

has not come to change the aggregate state of the substance (which in this work is proved that it is not correct) and from that an erroneous conclusion was drawn out that the supersaturated steam has stayed in clearly gaseous state, although it has entered deeply into the wet region. From this, an erroneous conclusion has followed and the up to now erroneous comprehension for the notion and definition of the metastable (processes and) states.

3. NEW THEORY OF THE SUPERSATURATION

In this work it will be proved that the process of supersaturated steam, the process A-3 in Fig. 2, is nothing else but only a process of the usual nonequilibrium wet steam in which during the expansion small nonequilibrium particles are formed condensate, K_1, K_2, K_3, K_4,... (see Fig. 4), consisted of two, three or only few agglomerated molecules, which due to the extreme velocity of proceeding the expansion process and due to the insufficient relaxation time in the nozzle cannot agglomerate together in order to form the corresponding quantity of bigger and equilibrium droplets condensate (consisted of a few hundreds molecules). During such an expansion small nonequilibrium particles condensate grow absorbing new molecules from the expanding steam, as it is shown in Fig. 4, and stay in bigger and bigger thermodynamics' nonequilibrium with the rest mass of the gaseous phase of the supersaturated steam which goes on to expand on lower and lower properties up to the reaching of the end of supersaturation of the steam in the state 3, respectively up to the reaching of the corresponding Wilson line in the *h,s*-diagram (see Fig. 22 in the attachment 3). Due to that in particles condensate stay accumulated (in form of raised temperature of the particles condensate in relation to the rest expanding gaseous phase of the steam) one part of the disposal internal energy of the equilibrium wet steam, which the author of this work calls **enslaved energy**. This energy is represented in Fig. 5 with the doted area (A-2-h-g-3-A), and can be calculated as difference between the absolute works of the eventual process of equilibrium wet steam A-2 and the real process of supersaturated steam A-3, respectively as:

$$\Delta w = w_{A\text{-}2} - w_{A\text{-}3} = (u_A - u_2) - (u_A - u_3) =$$

$$= -u_2 + u_3 < 0 \qquad (1)$$

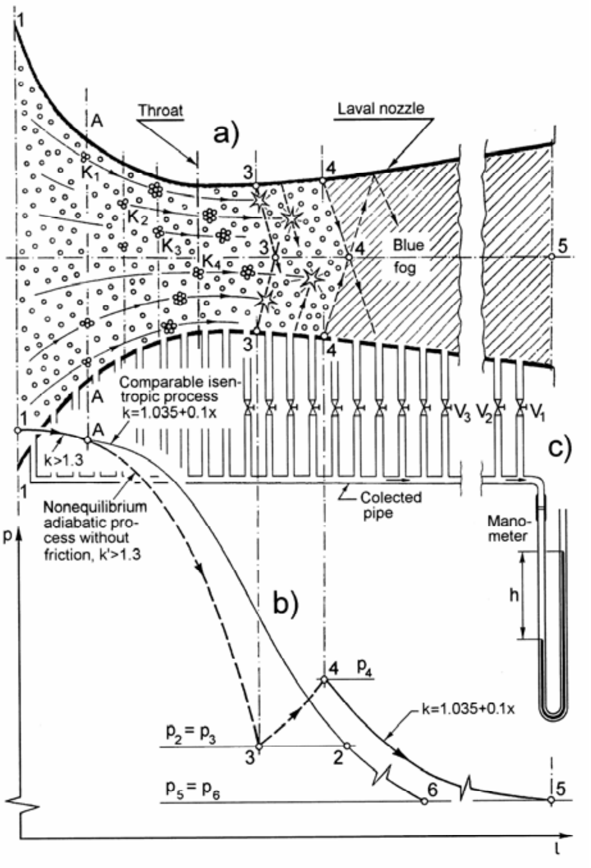


Fig. 4.
a) Figurative presentation of the forming and the breaking (the exploding) of the small nonequilibrium particles condensate, K_1, K_2, K_3, K_4,…, in Laval nozzle,
b) Schematically presentation of the fall of pressure at process with supersaturation of the steam 1-A-3-4-5 and at comparable isentropic process 1-A-2-6.
c) Measuring of the pressure along the nozzle with manometer and with opening of corresponding valve V_1, V_2, V_3,…etc.

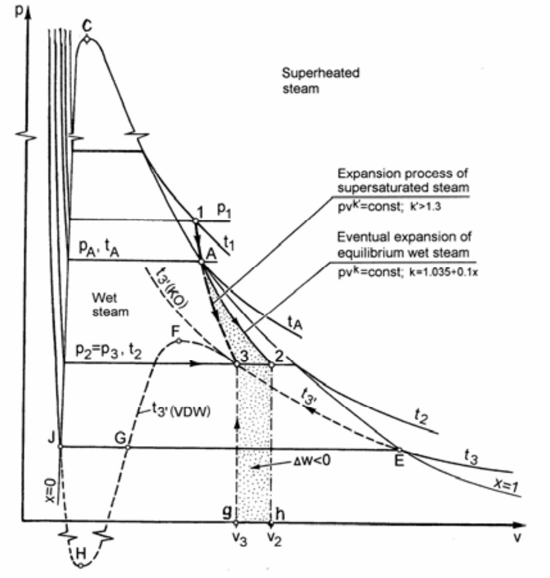


Fig. 5. Conditional presentation of the nonequilibrium process of the supersaturated steam A-3 in the equilibrium *p,v*-diagram

This enslaved energy is manifested to the surroundings as rejected heat, but that heat is not really rejected to the surroundings (because the expanding process is adiabatic), already, as we have seen above, it has stayed as enslaved energy or rejected heat toward the mass of the steam which expands. Due to that this energy we can call **enslaved energy** or **internal rejected heat** and can be expressed as:

$$\Delta w = q < 0, \text{ or } q = \Delta w < 0 \qquad (1a)$$

This energy can be represented, not only in the mechanical *p,v*-diagram (Fig. 5), but also in the heat *T,s*-diagram, as we shall see furthermore.

After reaching the end of supersaturation of the steam, in the state 3 (see Fig. 4) it comes to chain breaking (evaporating, or exploding) of the small nonequilibrium particles condensate of expanding steam in the space between the conical sections 3-3-3 and 4-4-4, therefore it comes to freed of enslaved energy from the particles, in the same quantity (1a), but with opposite sign, $q = \Delta w > 0$. This **freed energy** can be expressed through the relation of the first law of thermodynamics:

$$q = u_4 - u_3 + w_{3\text{-}4} > 0, \qquad (1b)$$

where the first part of that energy $u_4 - u_3$ is spent for increasing the internal energy of expanding steam from u_3 to u_4, due to that it comes to the appearance of the little pressure (and temperature) rise 3–4 in the nozzle (see Fig. 4) while the second part $w_{3\text{-}4}$ is spent for doing absolute work in the nozzle, or more exactly for acceleration of the steam in the nozzle. This absolute work $w_{3\text{-}4}$ is represented in Fig. 6 with the shaded area 3-4-i-g-3. (If it is supposed that the enslaved energy is freed in one moment then the rising process could proceed according to the vertical isometric process 3–4' (see Fig. 6) that is not the case here.)

The freed energy, $q = u_4 - u_3 + w_{3\text{-}4} > 0$, is manifested to the surroundings as internal added heat (although the rising process 3–4 is adiabatic). That is similar to the internal freeing of heat in the combustion processes at Otto machines. Due to that this energy can be called **freed energy** or **internal added heat**.

After reaching the end state 4 of the rising process 3–4 (see Figs. 4 and 6) the nonequilibrium wet steam becomes equilibrium, and from that state it goes on to expand in equilibrium condition and with forming of bigger droplets condensate consisted of few hundreds molecules up to the exit state 5. (Larger discussion for these processes is given in the attachment 3.)

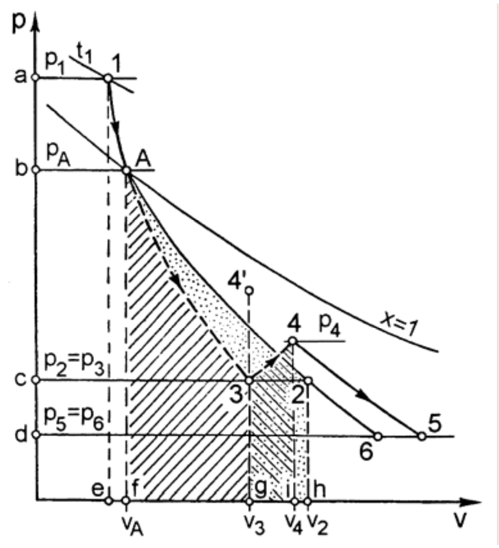


Fig. 6. Schematically presentation of the pressure fall along the Laval nozzle from Fig. 4 in *p,v*-diagram. This figure is joined by the point 4', dotted area (A-2-h-g-3-A) and shaded area (3-4-i-g-3).

4. ANSWER TO SOME IMPORTANT QUESTIONS

4.1. First question

As opposition of this (author's) supposition that during the process of supersaturation A-3 (Fig. 4) the above mentioned small nonequilibrium particles condensate are formed, the next justified question could be put: "Why these small particles condensate be seen at the standard experiments with cannot axially illuminated transparent Laval nozzles, which have been done by many authors (see Ref. [2, 13, 14], etc.)"?

The author's answer to this question is the following: These small particles condensate cannot be seen at the standard experiments because they, as groups of agglomerated molecules, consisted of two, three or only few molecules, are so small, that they are smaller than the waved length of the light with which they are illuminated axially in the nozzles. At those experiments only the bigger and equilibrium droplets condensate can be seen, consisted of few hundreds molecules, which are formed after reaching the little pressure rise 3–4 in the nozzles, and which can be seen with eyes only in form of **blue fog** (see Fig. 4).

4.2. Second question

The author will also try to give an answer to the next question: "Why does it come to chain breaking (evaporating, or exploding) of the small nonequilibrium particles condensate in the space between the conical sections 3-3-3 and 4-4-4 in the nozzle (see Fig. 4)?

The author's answer to this question would be the next: As it was said above during the expansion process in the nozzle the small nonequilibrium particles condensate grow by absorbing new molecules from the expanding steam (Fig. 4), and stay in bigger and bigger nonequilibrium with the rest expanding gaseous phase of supersaturated steam which goes on to expand on lower and lower properties. Somewhere after the throat of the nozzle (at $Ma > 1$) the particles condensate reach their biggest size at which they can still maintain as nonequilibrium particles. At these conditions the least disturbance can cause breaking (evaporating, or exploding) of the particles condensate. According to the author's opinion such disturbance appears in the form of sonic waves that form on the walls of the nozzle which cause the friction with the steam. Their sonic waves move from the walls to the central axis (as the arrows show in the Fig. 4) and in that manner form space between the conical section 3-3-3, at which the first small nonequilibrium particles condensate start to break (evaporate, or explode), while the section 4-4-4 when the process is finished. Between these two sections the enslaved energy from the exploded particles condensate is freed and therefore it comes to the appearance of the little pressure rise 3–4 in the nozzle. In the same space and at the same time it comes to mixing of the hotter molecules of exploding particles condensate and the cooler molecules of expanding gaseous phase of the steam and from them the mixture of molecules from which is formed the equilibrium droplets condensate are formed, consisted of few hundreds molecules, which can be seen with eyes (as we said before) in the form of blue fog only (see Fig. 4). As support of this author's supposition the explanations and the experiments attached in Ref. [2], pages 187 to 202, can be taken in consideration.

5. DRAWING AND CALCULATION OF THE NONEQUILIBRIUM PROCESS OF SUPERSATURATED STEAM

5.1. Drawing the supersaturated process A-3

This process and the end state of this process 3 in the equilibrium diagrams must be looked for somewhere under the limit curve of saturation $x = 1$, but not in the intersection of the equilibrium straights of the wet steam, p = const, t = const and v = const, already in the intersection of nonequilibrium extensions of the equilibrium isobars, isotherms and isometrics from the superheated region.

In order to get clearer which extensions are in question, let us remind ourselves that, for example, in the equilibrium *h,s*-diagram the isobars, the isotherms and the isometrics of the real gases are continuous curves through the whole superheated region until the limit curve of saturation $x = 1$, where it comes to refraction of these curves. After that, downwards in the wet region, these curves turn into straight lines, at which the isobars and the isotherms turn into common straight lines, p = const, t = const. In Fig. 7 three such equilibrium curves, p_1 = const, t_1 = const and v_1 = const are shown, which in the wet region turn into straight lines, p_1 = const, t_1 = const and v_1 = const. If the equilibrium curves, p_1 = const, t_1 = const and v_1 = const, from the superheated region are extended with the same angle and the same curvature downwards in the *h,s*-diagram, from the limit curve of saturation $x = 1$ to the wet region ($x < 1$), the **nonequilibrium extensions** of these curves will be obtained, marked with the dashed curves $p_{1'}$, $t_{1'}$ and $v_{1'}$ in Fig. 7. These dashed curves represent the properties of the nonequilibrium wet (or supersaturated) steam in the equilibrium *h,s*-diagram. It means that the nonequilibrium extensions are extended so as the region of equilibrium wet steam does not exist.

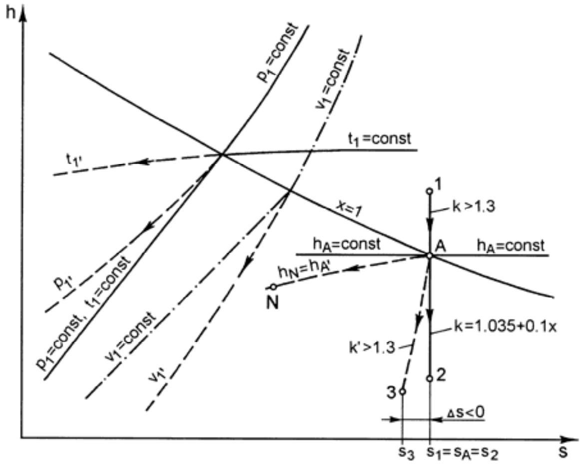


Fig. 7. Drawing the nonequilibrium curves of supersaturated steam p_1', t_1' and v_1' as continuous extensions of equilibrium curves p_1 = const, t_1 = const and v_1 = const from the superheated region

From this a conclusion follows that the properties of the supersaturated steam are found in the same region, under the limit curve $x = 1$, where the properties of the equilibrium wet steam are also found, but the reading of the first or other properties will be done from the corresponding curves $p_{1'}$, $t_{1'}$, $v_{1'}$ or p_1, t_1, v_1. Here it could be noticed that the nonequilibrium curves $p_{1'}$, $t_{1'}$ and $v_{1'}$ in Fig. 7, according to the numeric value, are equal to the values of equilibrium curves p_1, t_1 and v_1.

According to the same analogy, on the right side in Fig. 7, it is shown how it must proceed the equilibrium and nonequilibrium expansion processes 1-A-2 and 1-A-3 in the *h,s*-diagram, according to their exponents: the equilibrium process 1-A-2 with the exponents $k > 1.3$ and $k = 1.135 + 0.1x$, and the nonequilibrium process 1-A-3 with the exponents $k > 1.3$ and $k' > 1.3$. The same case is with the lines of the constant enthalpy where the dashed curve $h_{A'}$ represents the nonequilibrium extension of the equilibrium line h_A = const from the superheated region (see Fig. 7). From this figure it can be noticed that the numeric value of the enthalpy of supersaturated steam for some state *N* will not correspond to the value read on the left side of the scale in the *h,s*-diagram, because it smaller value than the real one will be read. In order the real value of h_N to be found out, one should go to the right along the curve $h_{A'}$ from the state N up to the state A, and in that point the values $h_N = h_{A'} = h_A$ to be read.

Having in mind this explanation, the end state 3 of the nonequilibrium process A-3 in equilibrium *h,s*-diagram, will be possible to be found in the intersection of the nonequilibrium extensions of the following equilibrium curves: the isobar p_2, the isotherm t_3 and the isometric v_3 (see the dashed curves $p_{2'}$, $t_{3'}$ and $v_{3'}$ in Fig. 8). All these nonequilibrium curves intersect in the state 3 that represents the end state of the nonequilibrium process A-3, namely 1-A-3. (Such evaluating of the end state 3 of one nonequilibrium process A-3 in the real *h,s*-diagram is shown in the attachment 4.)

In the same Fig. 8, because of comparison, the equilibrium isentropic process 1-A-2, whose end state 2 lies on the equilibrium straights, p_2 = const, t_2 = const and v_2 = const. is drawn. This gives the answer to the question how it is possible the supersaturated steam to have the same pressure with the equilibrium wet steam $p_3 = p_{2'} = p_2$, while the temperature and the specific volume are smaller than those of the equilibrium wet steam, $t_{3'} < t_2$ and $v_{3'} < v_2$.

In the same manner not only the end state 3 can be drawn, but also every other state of the supersaturation process A-3, which lies between the pressures p_A and $p_3 = p_{2'} = p_2$.

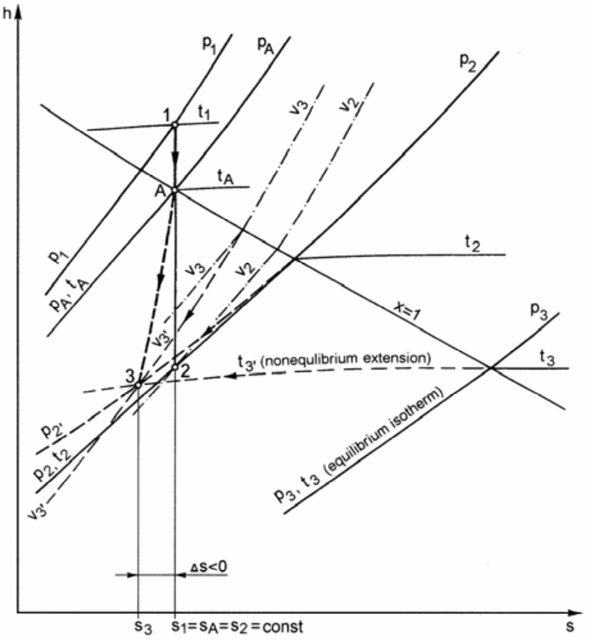


Fig. 8. Graphical determination of the end state 3 of the nonequilibrium process of supersaturated steam A-3 in equilibrium *h,s*-diagram in intersect of the nonequilibrium extensions $p_{2'}$, $t_{3'}$ and $v_{3'}$. This figure is totally compatible with the Fig. 4 in every their detail.

The nonequilibrium state 3 can also be drawn in the equilibrium *T,s*-diagram (Fig. 9 [10, 11]) in intersection of the isotherm $T_3 = T_{3'}$ and the extensions of the isobar $p_{2'} = p_2$ and the isometric $v_{3'}$ from the superheated region (see the dashed curves in Fig. 9). The shaded area $q < 0$, under the curve A-3, represents figuratively the part of disposal internal energy of the equilibrium wet steam $q = \Delta w < 0$, which stays enslaved (or rejected) to the extreme small nonequilibrium particles condensate (This area is equal to the doted area in *p,v*-diagram in Fig. 5.) In the same figure, due to comparison, and the equilibrium isentropic process 1-A-2, whose end state 2 lies on the equilibrium straights p_2 = const, t_2 = const and v_2 = const is also drawn.

The drawing of the nonequilibrium state 3 in the equilibrium *p,v*-diagram is shown in Fig. 5. The state 3 is found in the intersection of the isobar $p_3 = p_2 = p_{2'}$, the isometric vertical line $v_3 = v_{3'}$ and the extension $t_{3'}$ of the isotherm t_3 from the superheated region (see Fig. 5). The doted area in Fig. 5, marked with $\Delta w < 0$, represents figuratively the same enslaved internal energy into the extreme small nonequilibrium particles condensate as in Fig. 9, because of that is $\Delta w = q < 0$. In the same figure, due to comparison, the equilibrium isentropic process 1-A-2, whose end state 2 lies on the equilibrium straights p_2 = const, t_2 = const and v_2 = const. is also drawn.

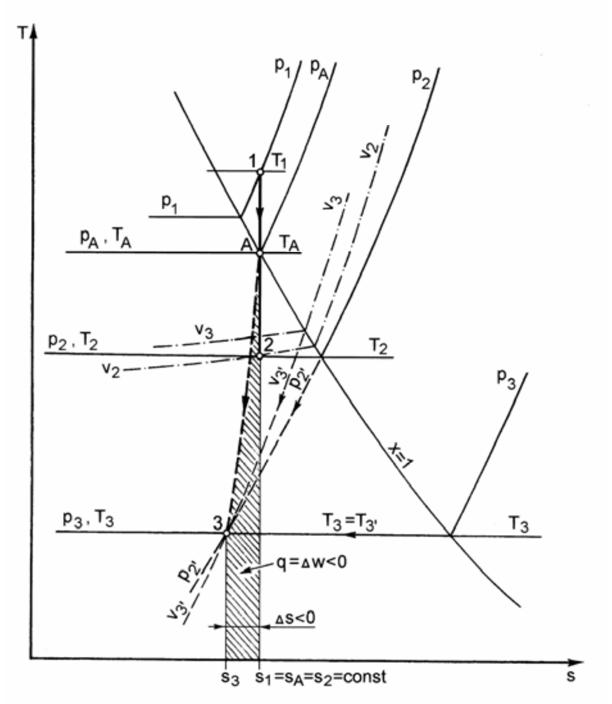


Fig. 9. Graphical determination of the end state 3 of the nonequilibrium process of supersaturated steam A-3 in equilibrium T,s-diagram in intersect of the nonequilibrium extensions $p_{2'}$, $T_3 = T_{3'}$ and $v_{3'}$. This figure is totally compatible with the Figs. 8 and 4 in every their detail.

From the comparison of the flow of processes 1-A-3 and 1-A-2 in all three diagrams (Figs. 5, 8 and 9) it has been seen that everywhere total mutual accord is reached from where it can be concluded that the nonequilibrium part A-3 of the process 1-A-3 proceeds exactly as it is previously described.

5.2. Calculations of the supersaturated process A-3

These calculations will consider:

– first, the manner of numeric evaluations of the exact value of the exponent of the curve of supersaturated steam A-3,

– second, evaluation of the enslaved energy at the process A-3, and

– third, calculation of the properties in the end state of supersaturation 3.

5.2.1. Evaluation of the exact value of the exponents k

In chapter 2 it was said that the up-to-now authors accepted the next values for the exponent of superheated (k) and supersaturated (k') steam: $k = k' = 1.3$. But these values are not quite exact, due to that it cannot be expected those results which are shown in Figs. 5, 8 and 9 to be obtained. Or in other words, these values of the exponents cannot reach all nonequilibrium extensions $p_{2'}$, $t_{3'}$ and $v_{3'}$ to intersect in the same state 3.

Now the following question can be put: How can the exact value of the exponent of supersaturated steam k' be determined?

This value can be determined empirically, giving different values of k' bigger than 1.3, until the exact value is being found.

But, at the calculation of numeric examples the author has found that the exact value of the exponent of supersaturated steam k' is very much in accord with the value of k on the limit curve of saturation $x = 1$, namely in the state A (p_A, t_A, v_A), according Fig. 5 and the diagram in Fig. 20 in the attachment 1. So, for example, for $p_A = 1$ kp/cm$^2 \approx 1$ bar and $t_A = t_s \approx 100$ °C from the diagram the value $k = k' = 1.38 > 1.3$ is read at which it achieves approximately the exact intersection of all three curves ($p_{2'}$, $t_{3'}$, $v_{3'}$) in one point, in the point 3, as in the h,s-diagram and in the T,s-diagram, or more exactly as in Figs. 8 and 9.

According to that, in order not to get lost time during the looking for the exact value of k', the author recommends, as the first starting value to be accepted the value k' which obtains as the ratio of the real specific heat capacities c_p and c_v for the properties in the limit state of the saturated water steam A (p_A, t_A, v_A), see Figs. 5 and 20, which means the exponent k' to be looked for as the ratio:

$$k' = \frac{c_p}{c_v}, \tag{2}$$

where the data for c_p and c_v in the equation (2), on the basis of which the Fig. 20 is drawn, are taken from Ref. [4], pages 440 and 441. If we are not satisfied with obtained results with this value of k', we can found the exact value of k' by giving different values for k' bigger than that calculated from the equation (2).

5.2.2. Calculation of enslaved energy

As it was explained in the chapter 3 the enslaved energy in the small particles condensate is calculated as a difference between the absolute works of comparable isentropic process A-2 and the real process of the supersatutated steam A-3, see equation (1). This difference in Figs. 5 and 6 is represented with the dotted area.

The absolute works $w_{A\text{-}2}$ and $w_{A\text{-}3}$ in relation (1), at condition $p_3 = p_2 = p_{2'}$ and $v_3 = v_{3'}$, can be calculated according to the next relations, which with the indexes in Fig. 5 should be:

$$w_{A-2} = \frac{1}{k-1}\left(p_A v_A - p_2 v_2\right), \tag{3}$$

and

$$w_{A-3} = \frac{1}{k'-1}\left(p_A v_A - p_3 v_3\right), \tag{4}$$

where k is the exponent of the isentropic process A-2, which is calculated according to the empirical formula of Zeüner as:

$$k = 1.035 + 0.1x = 1.035 + 0.1\left(\frac{x_A + x_2}{2}\right), \tag{5}$$

where x is the average value of the dryness $x_A = 1$ and $x_2 < 1$ of equilibrium steam in the states A and 2, while k' is the exponent of nonequilibrium adiabatic process A-3, which is calculated according to the equation (2), or as it was explained before.

For calculation the dryness in the state 2 the pressure in the state 2 must be known. This pressure can be treated as known because it is equal to the end pressure of supersaturated steam:

$$p_3 = p_2 = p_{2'}, \tag{6}$$

and can be read, for example, from the position of the corresponding Wilson line in the *h,s*-diagram (see Fig. 22 in the attachment 2), as end pressure, before the appearance of the little pressure rise in the corresponding nozzle. In this manner determined pressure $p_3 = p_2$, the dryness x_2 can be determined (at condition s = const) from the *h,s*-diagram or analytically.

5.3.3. Evaluation of the properties in the end states

To use the equations (3) and (4) the properties in the starting state A and in the end of the corresponding states 2 and 3 are needed, according to Fig. 5. These properties are determined as it follows:

– the properties in the state A, p_A and v_A (Fig. 5) can be treated as known because they can be calculated from the isentropic part of the process 1-A in the standard manner;

– the end specific volume of the equilibrium wet steam in the state 2, at the calculated exponent k, according to the equation (5), follows from the isentropic relation:

$$v_2 = v_A\left(\frac{p_A}{p_2}\right)^{\frac{1}{k}}; \tag{7}$$

– the end specific volume of the supersaturated steam in the state 3, at the calculated exponent k', according to the equation (2), follows from the adiabatic relation:

$$v_3 = v_A\left(\frac{p_A}{p_3}\right)^{\frac{1}{k'}}. \tag{8}$$

With properties found in the states 2 and 3 the absolute works at the processes A-2 and A-3 can be calculated, according to the relations (3) and (4), and at least the enslaved energy as their difference, according to the relation (1).

6. CALCULATIONS
OF THE RISING PROCESS 3–4

6.1. Short repetition

As it was said in the chapter 3, after reaching the end of the supersaturation in the state 3 (see Fig. 4), it comes to exploding the small nonequilibrium particles condensate in the space between the conical sections 3-3-3 and 4-4-4, therefore it comes to freed enslaved energy from the particles, in the same quantity (1a), but with the opposite sign, $q = \Delta w > 0$. This freed energy is expressed through the relation (1b), respectively $q = u_4 - u_3 + w_{3\text{-}4} > 0$, where the first part of the energy $u_4 - u_3$ is spent for increasing the internal energy of expanding steam from u_3 to u_4, due to that it comes to the appearance of the little pressure (and temperature) rise 3-4 in the nozzle (see Fig. 4) while the second part is spent for doing absolute work $w_{3\text{-}4}$ in the nozzle, which is represented in Fig. 6 with the shaded area 3-4-i-g-3. At the end of this short repetition it would be well to say that any graphical evaluation of the properties in the end state of the rising process 3-4 (according to the authors' opinion) is not possible. Here only analytical solution is possible that will be exhibited in the following text.

6.2 Preliminary calculation

In order to start any calculation of the properties in the end state 4, a possibility should be found for the analytical expression and calculation of absolute work which is obtained at the process 3-4. This work could be analytically calculated if it is supposed that for the process 3-4 (Fig. 6) the same relations of ideal gases as for the process A-3 can be used, but not with the adiabatic exponent *k*‘, already with adiabatic exponent *k*", which corresponds to the process 3-4.

This supposition could be accepted as possible because the process 3-4, also as the process A-3, for which used these relations were, is proceeding in the same low pressure region of the wet steam. It means, that if for the supersaturating process A-3 the relations of ideal gases are applied successfully then why they could not be used for the rising process 3-4, too.

The only difficulty at using these known relations and for the rising process 3-4 is that the numerical value of the exponent *k*" is unknown. The magnitude of this exponent could be determined by the experimental results and the conditions that:

– the properties in the state 3 (p_3, v_3) are known from the previous calculations in chapter 5;

– the pressure after the rise p_4 (Fig. 6) can be treated as known, because it can be measured with the manometer as in Fig. 4, or to be read from any already made experiments, as those in Fig. 10, for the corresponding type of nozzle, as a product:

$$p_4 = \varepsilon p_1 , \tag{9}$$

where ε is the dimensional pressure ratio, while p_1 is the starting pressure of the steam in the entrance of the nozzle;

– the wetness of the steam in the equilibrium state 4, which is reached after the pressure rise 3-4, can also be measured. That measuring can be done, for example, according to the separation method, which is schematically shown in Fig. 11. This method is applied successfully not only in the laboratory, but also in the working condition, at turbines that are in power. The errors which appear at the measuring of wetness with this device are not bigger than ±2,5 %. The principle of work of this device is based on the physical separating of gaseous and liquid phase of the steam in the separators 1 and 2. The device works on the following manner: with a tiny pipe as in Fig. 11 the steam is taken out from the nozzle in that place in which we want to measure the wetness of the steam (in our case in the equilibrium state 4). The steam which is taken out in that way is led through the separators 1 and 2, in which, the difference in the weight of the gaseous and liquid phase of the steam appears and it comes to physical separating of drops condensate from the dry steam which further on is leading towards the condenser 3.

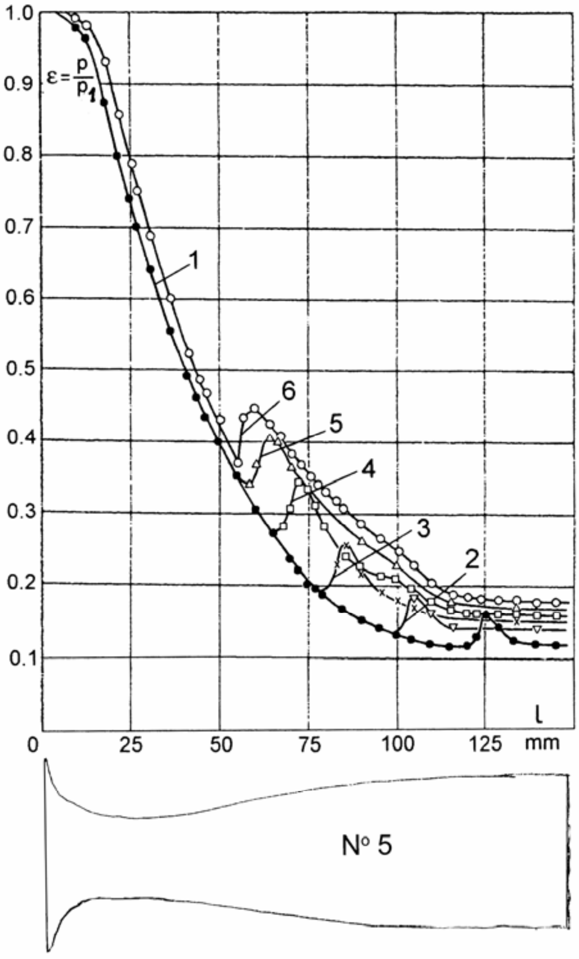


Fig. 10. Fall of pressure and appearance of the little pressure rise at expansion of water steam in convergent and Laval nozzles at different starting states of the steam: 1) Δt_1 = 77.4 °C, 2) Δt_1 = 56.4 °C, 3) Δt_1 = 33.5 °C, 4) Δt_1 = 15 °C, 5) y_1 = 0%, 6) y_1 = 5%, where: Δt_1 – degree of superheated steam, y_1 – starting moisture of the steam, $\varepsilon = p/p_1$ – pressure ratio between the pressure in any section p, and the entering pressure in the nozzle p_1, which is equal in the all 6 cases. (Taken from [2].)

By measuring the masses of condensated steam m_p, and the drops of liquid m_t (Fig. 11), the wetness of the steam is determined as ratio:

$$y = \frac{m_t}{m_p + m_t} , \tag{10}$$

or its dryness as $x = 1 - y$, or for the state 4:

$$x_4 = 1 - y_4 . \tag{11}$$

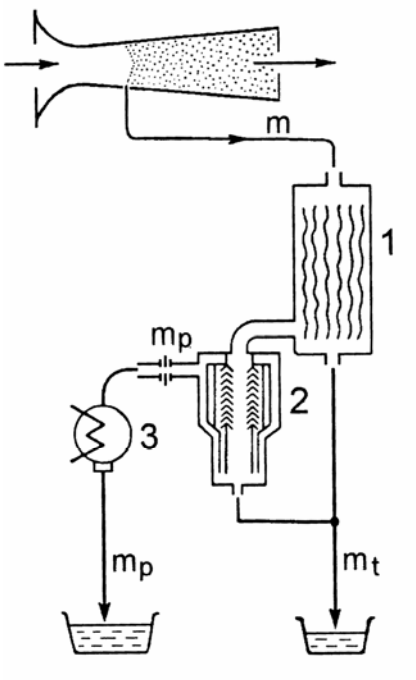


Fig. 11. Separating device for measuring of moisture of steam in the nozzles. (Taken from [2].)

In this manner, knowing the two measured properties of the steam in the equilibrium state 4 (p_4 and x_4) can be determined and the other properties in that state (v_4, h_4, s_4, u_4) through the known relations for the equilibrium wet steam, $v_4 = v'+x_4(v''-v')$, $h_4 = h'+x_4(h''-h')$, etc.

But, regrettably, in the literature that the author has at hand, measured values for the dryness of the steam after the pressure rise can not be found, although they, as it was previous said, can be measured. Therefore, in the further explanations looking for the simplest manner for calculation of the properties in the end of the pressure rise, in the state 4, it will be accepted that we have measured values, not only for the pressure rises as in Fig. 10, but also for the dryness of the steam in the end of these rises, too.

With such an acceptance, the calculation of the empirical exponent k'' of the rising process 3-4 for any experimental curve from the Fig. 10, will proceed in the following manner:

At first, for the chosen curve in Fig. 10, the pressure in the end of the rise will be determined, according to the relation (9), as $p_4 = \varepsilon p_1$, after which, at the experimentally known dryness x_4, see equation (11), the specific volume of equilibrium wet steam in state 4 could be determined, according to the relation for the equilibrium wet steam, $v_4 = v' + x_4 (v''-v')$. With these two experimental values, and the adiabatic relation placed for the rising process 3-4, $p_3 v_3^{k''} = p_4 v_4^{k''}$, the numeric value of the empirical exponent k'' could be calculated as:

$$k'' = \frac{\lg(p_3/p_4)}{\lg(v_4/v_3)}. \tag{12}$$

This exponent regularly has a negative value which moves in confines $-\infty < k'' < 0$, because the rising process 3-4 (Fig. 6) lies somewhere between the isochoric process $v_3 = v_{4'} = \text{const}$, whose exponent is $n = \to -\infty$, and the isobaric process $p_3 = p_2 = \text{const}$, whose exponent is $n = 0$. From this follows that the process 3-4 proceeds at the negative exponent $k'' < 0$ that is alike to the combustion process in the Otto machines.

After determining the value of the exponent k'' the absolute work $w_{3\text{-}4}$ which is acting during the rising process 3-4 (Fig. 6) could be calculated, according to the adiabatic relation:

$$w_{3-4} = \frac{1}{k''-1}\left(p_3 v_3 - p_4 v_4\right). \tag{13}$$

At the calculated $w_{3\text{-}4}$ and known amount of the total released (enslaved) energy $q = \Delta w > 0$ at the rising process 3-4, it will be able, on the basis of the relation (1b), to determine the part of the released energy which is spent to increase the internal energy of the steam from u_3 to u_4:

$$u_4 - u_3 = q - w_{3-4}. \tag{14}$$

By dividing the obtained absolute work $w_{3\text{-}4}$ and the total released heat at the rise, $q = \Delta w > 0$, their ratio could be determined:

$$\frac{w_{3-4}}{q} = Z, \tag{15}$$

which is mainly constant and characteristical for defining the type of nozzles as the exponent of the rise k'', too.

According to that, in this manner determined Z, and calculated $q = \Delta w > 0$, according to the equation (1), in future calculations the absolute work which is obtained at the rising process 3-4, as product of Z and q can easily be determined:

$$w_{3-4} = Z\,q, \tag{16}$$

while the increase of the internal energy of steam at the rise 3-4 as:

$$u_4 - u_3 = (1-Z)\,q, \tag{17}$$

which is clear that their sum must be equal to the total released heat $q = \Delta w > 0$ at the rise 3-4:

$$Z\,q + (1 - Z)\,q = q = \Delta w\ . \qquad (18)$$

If at the determination of Z and k'' we want to achieve bigger average exactness for the observed nozzle then we should repeat the previous calculation for the 6 expansion curves in Fig. 10, namely for the curves 1, 2, 3, 4, 5 and 6 and from the obtained results for Z_1, Z_2, Z_3, Z_4, Z_5, Z_6 and $k_1'', k_2'', k_3'', k_4'', k_5'', k_6''$ to find the arithmetic average for Z and k'' as:

$$Z = \frac{Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6}{5}\ , \qquad (19)$$

and

$$k'' = \frac{k_1'' + k_2'' + k_3'' + k_4'' + k_5'' + k_6''}{5}\ . \qquad (20)$$

6.3. Final calculation of the properties in the end of the rise

In this way determined values for Z and k'' the analytical calculation for the corresponding type of nozzle (for which the values Z and k'' are found) would be acting in the following manner.

First, in the previously described manner the exponent of supersaturated steam k' and the properties of supersaturated steam in the end state of supersaturation 3 (p_3, v_3) would be determined. After that, according to the equation (1) the enslaved energy of the steam $\Delta w = q < 0$ would be calculated, which is equal to the released energy $\Delta w = q > 0$ at the rising process 3-4, after which, according to the relation (16), the part of released energy would be found, which is transformed in the absolute work at the rising process 3-4:

$$w_{3\text{-}4} = Z\,q\ . \qquad \text{(a)}$$

At known numeric values of $w_{3\text{-}4}$ and k'' the relation (13) can be placed, respectively:

$$w_{3\text{-}4} = \frac{1}{k''-1}\left(p_3 v_3 - p_4 v_4\right)\ , \qquad \text{(b)}$$

in which p_3 and v_3 are unknown. On the other hand between the properties in the states 3 and 4 is valid adiabatic relation, from which one of the both unknown in relation (b) can be expressed as:

$$v_4 = v_3 \left(\frac{p_3}{p_4}\right)^{\frac{1}{k''}}\ , \qquad \text{(c)}$$

and with the change of (c) in (b) the relation (b) is obtained in which only one unknown exists, respectively the pressure after the pressure rise p_4:

$$w_{3\text{-}4} = \frac{1}{k''-1}\left[p_3 v_3 - p_4 v_3 \left(\frac{p_3}{p_4}\right)^{\frac{1}{k''}}\right]\ . \qquad \text{(d)}$$

By rearranging of (d) the definitive relation for calculation of the end pressure p_4 of the rise 3-4 (Fig. 6) in Pa can be obtained:

$$p_4 = \left[\frac{p_3 v_3 - w_{3\text{-}4}\left(k''-1\right)}{v_3 \left(p_3\right)^{1/k''}}\right]^{\frac{k''}{k''-1}}\ . \qquad (21)$$

With the change of the found p_4 in relation (c) the specific volume of the equilibrium wet steam in the end state 4 is obtained as:

$$v_4 = v_3 \left(\frac{p_3}{p_4}\right)^{\frac{1}{k''}}\ . \qquad (22)$$

From the known relation for the specific volume of the equilibrium wet steam, in this case placed for the state 4, $v_4 = v' + x_4 (v'' - v')$, the dryness of the steam in that state can be determined:

$$x_4 = \frac{v_4 - v'}{v'' - v'}\ , \qquad (23)$$

and with it the rest properties in the equilibrium state 4, through the known relations:

$$h_4 = h' + x_4 (h'' - h')\ , \qquad (24)$$

$$s_4 = s' + x_4 (s'' - s')\ , \qquad (25)$$

where v', v'', h', h'', s', s'' can be determined (with interpolation) from the steam tables.

With these properties the state 4 and its position in the equilibrium diagrams *i,s*, *T,s* and *p,v* is totally defined. From the state 4 and further on the process in the nozzle is solute standard and due to that it is not attached here.

In this manner, through the previous determining of the values Z and k'' for the determined type of nozzle, all phenomena which would appear in the defined type of the Laval nozzle, at expansion of slightly superheated, saturated or wet steam in them, could be, in advance (without measuring), anticipated and on the basis of that to do the correct heat calculation which will represent the basis for its dimension and construction.

If the angle of ascend of the pressure rises in Fig. 10 is compared with the angle of ascend of the pressure rises for the other Laval nozzles (see, for example, the Laval nozzle shown in Fig. 12) it could be noticed that between them these is a big similarity. It leads to the thought that the characteristic constants Z and k " found for one type of the Laval nozzle could be used with sufficient exactness and for any other type of Laval nozzles.

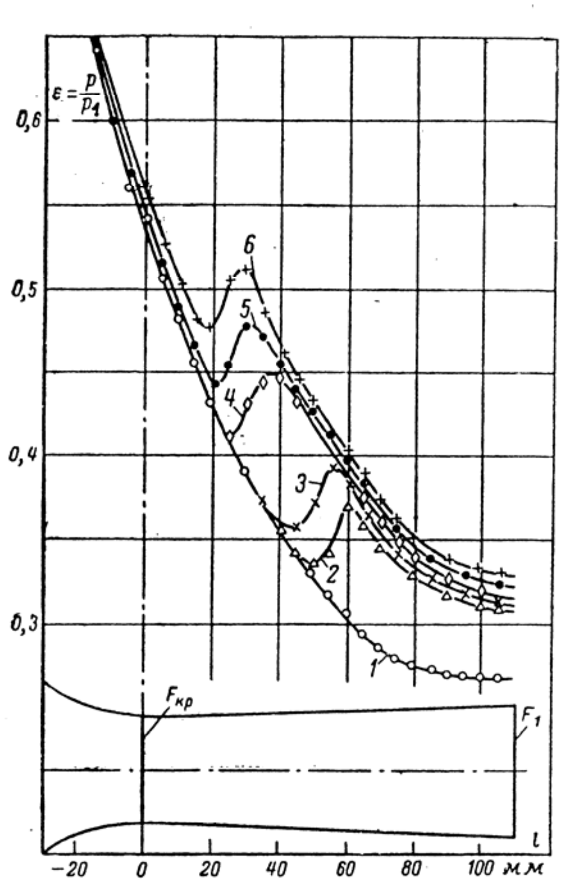


Fig. 12. Fall of pressure and appearance of the little pressure rise at expansion of water steam in plane Laval nozzle at different starting states of the steam: 1) $\Delta t_1 = 163\ ^{\circ}\mathrm{C}$, 2) $\Delta t_0 = 123\ ^{\circ}\mathrm{C}$, 3) $\Delta t_1 = 117\ ^{\circ}\mathrm{C}$, 4) $\Delta t_1 = 106\ ^{\circ}\mathrm{C}$, 5) $y_1 = 3\%$, 6) $y_1 = 4\%$, where Δt_1, y_1 and $\varepsilon = p/p_1$ are the same as in Fig. 10. (Taken from [2].)

It would be well to discuss the Fig. 13, which is drawn on the basis of data of the pressure rises in Fig. 10. From this figure it can be seen that the magnitude of the pressure rises in Fig. 10 depends on the magnitude of released energy $\Delta w = q > 0$ at the rising processes 3-4 (see the dotted areas $\Delta w = q > 0$ in Fig. 13 for the corresponding curves 1, 2, 3, 4, 5 in Fig. 10). From this comparison it is seen that the pressure rise is the biggest for the saturated steam (for the curve 5) because for that curve the dotted area is the biggest. It means that by superheating the steam the process of supersaturation starts later therefore the rise appears deeper in the nozzle and is smaller, see the curves 4, 3, 2, 1. From the Figs. 10 and13 it can also be seen that the magnitude of the pressure raises decreases with decreasing of the dryness of the steam, see the curve 6 in Figs. 10 and 13. In this case the rise is smaller because with decreasing of the dryness of the steam and the dotted area decreases. For this case the Wilson line W in Fig. 13 is translated downward in the p,v-diagram on the new lower position W'. This whole discussion is also totally valid for the pressure rises in Fig. 12.

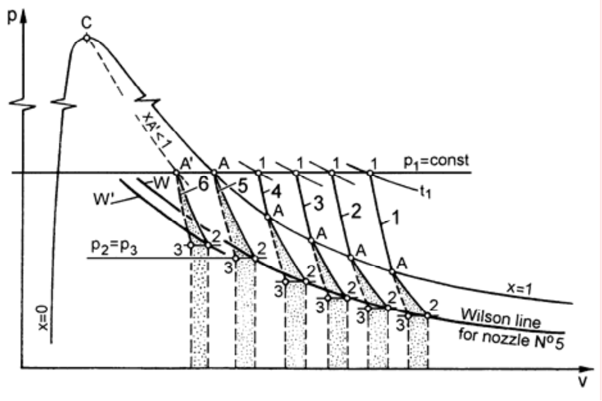


Fig. 13. This figure corresponds to the pressure rises in Fig. 10 which shows how the magnitude of the pressure decreases rises along the axis of the nozzle depending on the initial superheating or initial moisture of the steam

7. PROOFS FOR VALIDITY OF THE FIRST AND SECOND LAW OF THERMODYNAMICS THROUGH THE NEW THEORY OF SUPERSATURATION

A comparison will be made between the nonequilibrium process 1-A-3-4-5 (Fig. 14), which proceeds with supersaturation of the steam in the part A-3 and the pressure rise in the part 3-4, with an eventual equilibrium isentropic process 1-A-2-6 which would proceed from the same initial state 1 to the same exit (surrounding) pressure $p_5 = p_6 = p_{\mathrm{surr}}$. At this explanation the friction is neglected in all parts of the mentioned processes.

This comparison will be made to prove that the first and the second law of thermodynamics are fully valid as for equilibrium also and for nonequilibrium processes and that all which was explained and proved in the previous chapters for the phenomena of supersaturated steam which is based on these two laws.

In this comparison the following question arises as fundamental: In which place of the pressure rise will the new equilibrium state of steam reach? a) In the state M which lies on the isentropic process 1-A-2-6 (see Fig. 14) or b) in the state 4 which lies over the isentropic process 1-A-2-6.

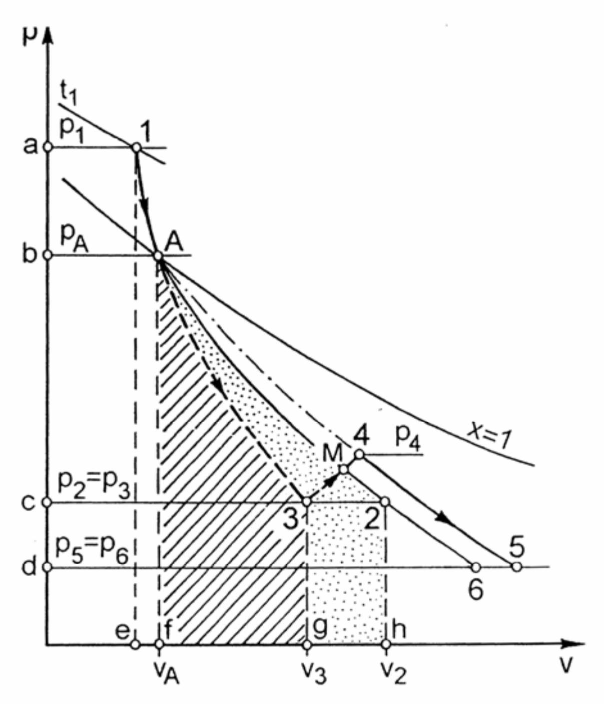


Fig. 14. Repeating of Fig. 6 joined by the important point M in *p*,*v*-diagram

a) If it is assumed that the new equilibrium state after the pressure rise will be reached in the state M, which lies on the isentropic process 1-A-2-6, an error will be involved in respect to the first law of thermodynamics due to the released enslaved energy $\Delta w = q > 0$ and eventual reversal of the nonequilibrium process A-3 in equilibrium condition through the nonequilibrium rise 3-M, a part of the available energy of the steam represented with the area (A-M-3-A) = Δw_t, would remain permanently lost. In order to make this clearer it could be assumed that in the nozzle the following two processes proceeded: the equilibrium, purely isentropic process from 1 through A-M-2 to the exit state 6 and the nonequilibrium process from 1 through A-3-M to 6. From this discussion it comes out that both processes started from the same initial state 1 and ended in the same exit state 6, reaching totally the same exit values (p_6, t_6, h_6,... etc.), but the process 1-A-3-M-6 provides less technical work in relation to the process 1-A-M-2-6 for the amount of the area Δw_t = (A-M-3-A). From here it follows that during the proceeding of the nonequilibrium process 1-A-3-M-6 a part of the energy system in the amount Δw_t = (A-M-3-A) is permanently lost, which is inadmissible from a viewpoint of the law for conservation of energy, i.e. the first law of thermodynamics, according to which the energy in a system must always be constant. It means, if a part of the energy in any system is "lost" this part should immediately and in the same amount appear in some other form (as for example, in form of an increased heat energy of the system or in some other form), which was not the case with the considered assumption in which **the energy loss of the system** Δw_t = (A-M-3-A), **is permanent**. For these reasons, it is not reasonable to consider this case further, from a viewpoint of the second law of thermodynamics, when the first law is not satisfied.

b) The first and the second law of thermodynamics would be fully satisfied if only an assumption is made that the nonequilibrium process A-3 would be equilibrated, due to the released enslaved energy $\Delta w = q > 0$, at the proceeding of the nonequilibrium rising process 3-4, whose final state 4 lies somewhere above the isentropic curve 1-A-2-6. Therefore, all properties of the newly created equilibrium wet steam in the state 4 (p_4, t_4, v_4, u_4, h_4, s_4) must be bigger than those in the state M, which lies on the isentropic curve 1-A-2-6, in order to have an accurate energy balance (without a permanent energy loss) not only during the equilibrium process 1-A-2-6, but too during the nonequilibrium process 1-A-3-4-5, also. From here it follows that the new equilibrium state after the pressure rise (4) should lie on a bigger isentropic curve $s_4 > s_1 = s_6$ = const in relation to the equilibrium process 1-A-2-6; in this case and the enthalpy of the steam in the exit state 5 should be bigger than the one of the equilibrium exit state 6, $h_5 > h_6$ (see Figs. 14 and 15).

From the comparison of the technical works which would be obtained from the equilibrium process 1-A-2-6 (Figs. 14 and 15):

$$w_t = (\text{a-1-A-2-6-d-a}) = h_1 - h_6, \qquad \text{(a)}$$

and the nonequilibrium process 1-A-3-4-5:

$$w_t' = (\text{a-1-A-3-4-5-d-a}) = h_1 - h_5, \qquad \text{(b)}$$

it is clearly seen that the nonequilibrium process gives less technical work for the amount:

$$\Delta w_t = w_t - w_t' = h_5 - h_6 \,. \qquad \text{(c)}$$

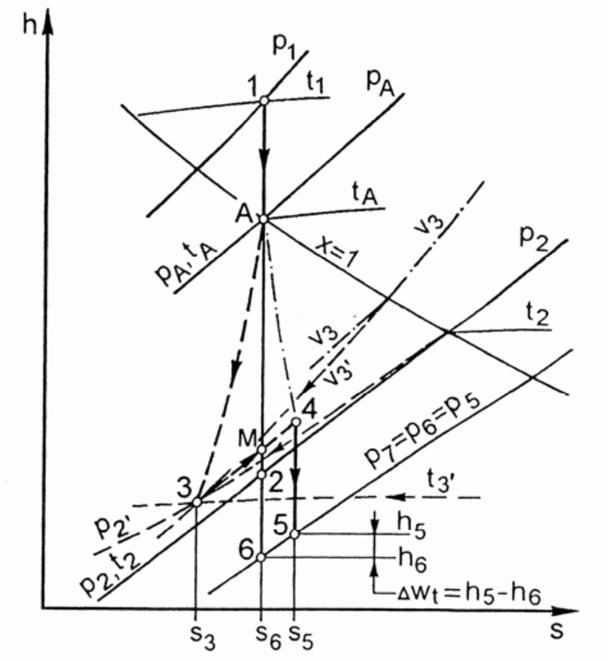


Fig. 15. The same as in Fig. 14 but transferred in *h,s*-diagram

In this manner, besides the first law, and the second law of thermodynamics is simultaneously satisfied, too, because at totally equal energy balance in both processes, the nonequilibrium process 1-A-3-4-5 (due to the nonequilibrium in its parts A-3 and 3-4) gave smaller technical work for Δw_t and a steam with bigger exit enthalpy $h_5 = h_6 + \Delta w_t > h_6$ at simultaneous total increase of the entropy of the system, $\Delta s = s_5 - s_1 > 0$, in relation to the system of the equilibrium process 1-A-2-6 in which $\Delta s = s_6 - s_1 = 0$.

From this discussion it has been seen that the part which has non been obtained as a technical work from the process 1-A-3-4-5 has not been lost anywhere since it is obtained as a heat energy at the exit of the system. According to that, the part Δw_t will represent this part from the total available theoretical technical work of the system $\Delta w_t = h_1 - h_6$, Eq. (a), which is degraded (it left the system in a form of low-quality heat energy) due to the nonequilibrium proceeding of the parts A-3 and 3-4 in the process 1-A-3-4-5. This degradation of energy, according to the second law of thermodynamics, which is known as a law of degradation of energy, leads to total increase of entropy of the system (in which the nonequilibrium process 1-A-3-4-5 is proceed) for the amount:

$$\Delta s = s_4 - s_A = s_5 - s_1 > 0. \qquad \text{(d)}$$

The nonequilibrium parts A-3 and 3-4 of the process 1-A-3-4-5 up-to-now, maintly from practical reasons, have been considered separately in order to be able from the first part A-3 to calculate the exponent k', the properties in the state 3 and the quantity of the enslaved energy $\Delta w = q < 0$, while from the second part 3-4 to define the ratio Z, the exponent k'' and the properties in the state 4. However, from a view point of the second law, these two nonequilibrium parts should always be considered as an unity A-3-4. Then, it becomes quite clear why at the proceeding of the total nonequilibrium process A-3-4 the entropy of the system is increasing for $\Delta s = \Delta s_{\text{resultant}} = s_4 - s_A > 0$, although in the first part A-3 it decreases for $\Delta s_{A\text{-}3} = s_3 - s_A < 0$, due to $\Delta w = q < 0$, while in the second part 3-4 it increases for $\Delta s_{3\text{-}4} = s_4 - s_3 > 0$, due to $\Delta w = q > 0$. This conclusion in essence follows from the known fact that the change of a property of state does not depend on the way of change but only on the magnitude of the properties in the initial and final state of the process. This fact enables the nonequilibrium parts A-3 and 3-4 to represent through their fictive resultant process A-4 (see the curve dot-line in Figs. 14 and 15) from which it can be seen that the entropy of the system at proceeding of the nonequilibrium process A-3-4, i.e. A-4, is steadily increasing (in this case for the amount $\Delta s = \Delta s_{\text{resultant}} = s_4 - s_A > 0$).

If we remember to that what was exceptionally emphasized at the beginning of this discussion that at comparison of the equilibrium and nonequilibrium processes 1-A-2-6 and 1-A-3-4-5, the friction was neglected in both processes, then it becomes clear that a process even and when the friction is completely neglected shall be irreversible if the whole mass of fluid is not in complete internal equilibrium.

In the thermodynamics many examples are known from which it can be seen very clearly the irreversible character of an actual process when the appearance of the friction comes to lose a part of the available technical work of the system, as for example, during actual expansion processes of fluids in nozzles, in piston machines and in other devices. However, up to now there is no example from which it can be seen so clearly (as in Figs. 14 and 15) the loss of a part of the available technical work of the system Δw_t and the irreversible character of the whole process as a result of the internal nonequilibrium of the fluid. The author is in opinion that the case of supersaturated steam, which is explained in this work, represents, now for now, the first and the most convincing example of the classical thermodynamics from which the irreversible nature of a process can be seen if at his proceeding (besides other conditions) and the condition for internal equilibrium of the fluid. is not fulfilled

8. SUMMARY OF THE UP-TO-NOW DISCUSSED PHENOMENA OF THE SUPERSATURATED STEAM

With the exhibitions in previous chapters the author of this work has confirmed the previously noticed (but not proved) nonequilibrium character of the supersaturated (metastable) steam. He has also proven why that steam is nonequilibrium and why after the supersaturation of the steam it comes to the appearance of that sudden pressure rise in the Laval nozzles, after which the steam begins to condense regularly. From these proofs the author's conclusion follows that the **metastable steam, such as it was up to now explained and defined, does not exist in reality** and therefore would be the best to give it a new, more corresponding name, as, for example, **nonequilibrium wet steam**, because up-to-now its name nothing has said to anybody, but only it has led to contradictions, confusions and mistakes.

9. OTHER EXAMPLES FOR EXISTING OF THE METASTABLE STATES

In this paper other examples for existence of metastable states in the substances, mentioned in the existing literature will be discussed shortly. Between them as more interest will be discussed the following:

9.1. Heating of droplets water dived into oil

The previously mentioned heavy contradictions about the up to now definitions of the metastable states, do not exhaust with the example of supersaturated steam, because in the literature (see Ref. [1], page 139) as a proof of existing of the metastable states is mentioned and the example of heating of droplets water dived into oil with same density as the water, Fig. 16, which have not evaporated up to temperature of 180°C, although the pressure (of the oil and droplets) has been approximate equal to the atmospheric pressure.

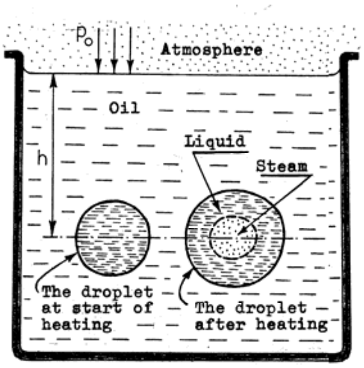


Fig. 16. Heating of droplet water dived into the oil with the same density as the water up to 180°C (??)

As far as this example is concerned, it is in principle totally contradictory in relation to the new comprehension for the nonequilibrium character of the metastable states, which follows from the extreme velocity of proceeding the expansion processes and from insufficient relaxation time. The contradiction of this example consists in it that the heating of the droplets water in oil is a remarkably a slow process (in relation to the extreme rapid process of supersaturation of the steam in the nozzles), but in literature it is mentioned as an example of metastable state. In this case we must ask ourselves what is metastable in it (??). That the droplets water have not evaporated up to 180°C **is only one illusion but not metastable process**, because for that nonevaporating it another, physically more acceptable explanation can be found.

Due to explanation of this appearance, the author of this work has analyzed three eventual processes, 1-2, 1-3 and 1-4, which are showed in Fig. 17.

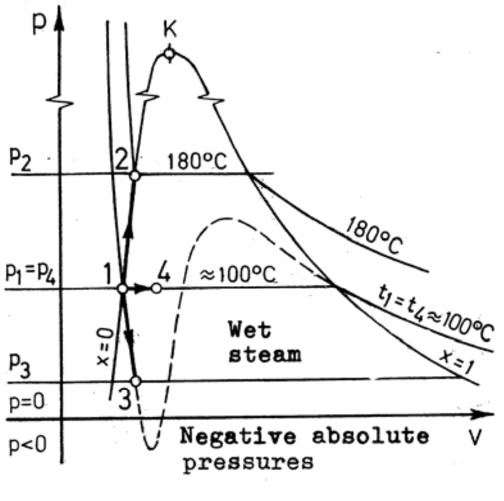


Fig. 17. Presentation of the eventual physically realizable processes, 1-2, 1-3 and 1-4, for the case shown in Fig. 16

The first of these three processes, namely the process 1-2, is physically not realizable because due to the heating of the droplets the pressure in the droplets must be 10,2 bar, or so big as it corresponds to the temperature of saturation of the water into the droplets of 180°C. Something like this is not possible because on the basis of all that is known up to now the membrane of the droplet could not stand such a big pressure in no case.

The second possible process, 1-3, or more precisely the Van der Waals' behavior of the droplets also is not physically realizable because the temperature in the droplets must stay constant (≈ 100°C) in relation to the surrounding oil which would reach temperature of 180°C. This is impossible due to the existing transfer of heat from the warm oil to the cooler water in the droplets. Besides it and the pressure in the droplets must also become lower and lower than the pressure of the surrounding oil (of ≈1 bar) with tendency to become negative (??) (see Fig. 17), which is extremely unbelievable, impossible and absurd.

As an unique physically realizable process in this case the process 1-4 is imposing, what shows that this case is only a bit an unusual example of capillary appearance, which can be explained with partially isobaric-isothermal evaporating of one part of the mass of the droplets water under the membrane of the droplets (see Fig. 16). In this case the membrane of every droplet would have the same role as a cylinder with free moving piston in which the water droplet is placed. In this manner, or more exactly, with transfer of heat from the warm oil toward the droplets and with partially evaporating of the water under the membrane of droplets, the membrane of droplets would expand and extend isobaric-isothermal (but no metastable) up to the exploding of the droplets, which would happen at atmospheric pressure and at the temperature (of mixture water-steam) in the droplets of ≈100°C, but not at the temperature of oil (and water) 180°C, as it seems at first sight. This shows that the exit at the explanation of any a bit unusual appearance must not be always looked-for in the metastable states.

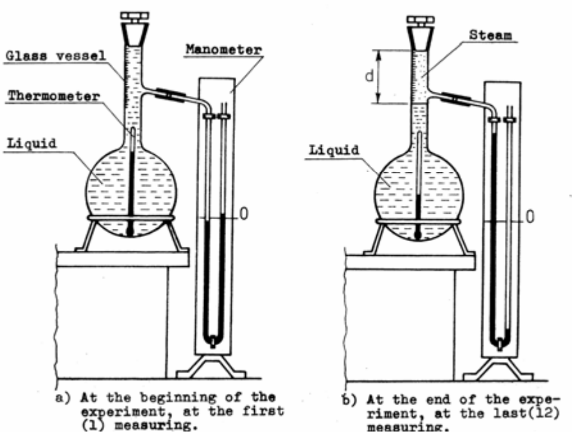
In this case it is interesting the note of those authors who mention this experiment (see Ref. [1], page 139) that it must be done very carefully because “the metastable" state would disintegrate earlier. However, according to the author of this work, this carefulness is not necessary due to some "specialty" of this experiment, but because the membrane of droplets is so weak that even at the smallest shock they could explode and at temperatures much lower than 180°C (and in such a case it could not reach the "metastable" state).

9.2. Cooling of water in little blinded glass ampoules

As one of the oldest examples for existence of the metastable states at the real substances, in literature the cooling of water in little blinded glass ampoules is mentioned (see Ref. [6], page 121), which was done by Berthelot (1850). From these experiments it has followed, not only that the metastable states are possible at the real substances, but that it is possible and that which in Physics was considered as absolutely unreal and impossible, or more exactly, **that and negative absolute pressures are possible** (see Ref. [6], page 121, and Ref. [9], page 119). Later (1873) because such pressures were announced by the famous Van der Waals equation (see Fig. 1) nobody dared to doubt or oppose correctness of those experiments.

As far as these proofs are concerned for the existence of negative absolute pressures into the ampoules, it could be said that these "proofs" have been proved only by calculation, on the basis of different coefficients of thermal extension of water and glass, which in principle must not be accepted as an experimental proof that they exist in reality (because they are not experimentally proved but only calculated). To this could be added that it was always noted that those experiments were done at some "special conditions” which include that the glass and water in the ampoules must be exceptionally clean and alike. However, nobody has asked about some more usual things, as, for example, why those experiments have been done in **little glass ampoules** in which nothing can be seen nor measured, but has not been observed, for example, the cooling of that same water in some bigger glass vessel where measuring instruments could be enclosed, and with real measurements (not with calculations) the existence of "that something" to be proved for which it was asserted that exists.

In this work the author has proved experimentally (with slowly isochoric cooling of saturated water in a bigger glass vessel, Fig. 18, a and b, which in principle is totally the same with the isochoric cooling of water in the ampoules) that the metastable states and negative absolute pressures (as those in Fig. 1) do not exist nor can exist, as it will be shown below.



a) At the beginning of the experiment, at the first (1) measuring.

b) At the end of the experiment, at the last(12) measuring.

Fig. 18. Slowly cooling of clean (redestilated) saturated water in a closed glass vessel

From the experiments which the author of this work has been doing with totally clean (redestilated) water in apparatus shown in Fig. 18, it can be seen clearly that the warm, or saturated liquid, which has been left to cool slowly in the closed vessel (see Fig. 18-a), after the free cooling in surrounding it has not stayed in a clear liquid state as in the ampoules, but it has evaporated (see Fig. 18-b) quite normally and according to all known laws of physics and thermodynamics. At that cooling, the pressure in the vessel was falling very low (see Table 1), but at none experiment it has showed tendency to become smaller than zero. It tends only toward zero, $p >> 0$, that is quite logical and lawful, but never has reached zero nor has passed zero. This can be clearly seen from the diagram in Fig. 19, which is drawn on the basis of data for p and t from Table 1 obtained from the measurements with the apparatus in Fig. 18. As information, the glass vessel in Fig. 18 has been equal to 2235 cm^3.

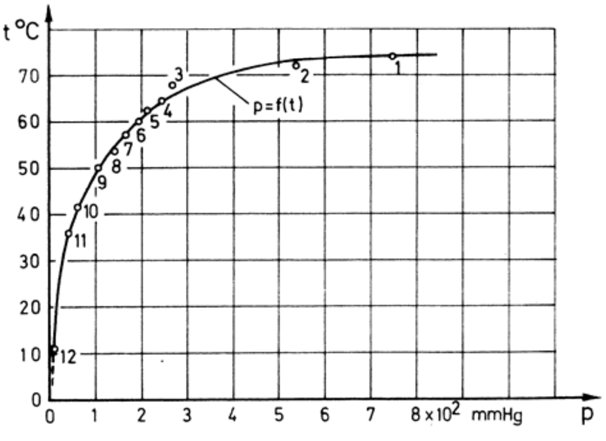


Fig. 19. The curve $p = f(t)$ obtained on the basis data from Table 1

Table 1

Measuring data from the experiment made with the apparatus shown in Fig. 18.

Number of measuring	Temperature in vessel t_0 °C	Quantity of steam d (mm)	Gage pressure p_p (mmHg)	Absolute pressure p (mmHg)
1	74.0	–	+15	750.6
2	72.0	–	–195	540.6
3	68.0	5	–465	270.6
4	64.5	12	–488	247.6
5	62.5	18	–517	218.6
6	60.0	23	–538	197.6
7	57.0	30	–569	166.6
8	53.5	40	–592	143.6
9	50.0	47	–628	107.6
10	41.5	63	–674	61.6
11	35.8	90	–695	40.6
12	11.0	106	–725	10.6

On day 5. IV. 1985 when this experiment was done the atmospheric pressure in Skopje was equivalent to $p_0 \equiv 735{,}6$ mmHg

From these (author's) experiments it has followed that "that" which has happened in the ampoules is an usual capillary appearance, which is so much stressed as the vessel (or the ampoule) in which the experiment has been done is smaller. However, and in the other hand at the isochoric cooling (or heating) of water in ampoules there is nothing metastable, because that process is very slow (and equilibrium) in relation to the flow of the supersaturated steam in the nozzles, which is proclaimed as a metastable process because that process is proceeding extremely rapidly, or more exactly, at insufficient relaxation time, which is not the case with ampoules.

In literature other examples can be found and for "existing" of metastable states at the real substances, as, for example, at the flowing of saturated liquid (water) through convergent nozzles. These examples should not be discussed in this work, due to saving space in the paper, although acceptable physical explanation could be found as for before discussed "metastable steam".

10. CONCLUSION

From all that has been said until now the author of this work concludes that all those things which could not have been explained up-to-now physically they have been thrown in the same basket for the metastable states.

The exit from this chaos, which has become due to the up-to-now contradictory definitions for the metastable states the author of this work has found in the physical explanation of all previously mentioned "special" processes, only from the aspect of equilibrium thermodynamics, which distinguishes only two states, equilibrium and nonequilibrium states, and no more. On the basis of those explanations the author of this work has come to the conclusion that **the metastable states such as they were defined and comprehended up to now do not exist in reality**. According to that, all those before mentioned special (processes and) states that have looked like metastable states are nothing else but only usual nonequilibrium (or equilibrium) wet steam. Depending on this conclusion the author of this work believes that in this work a totally clear and lawful answer is given to many fundamental questions on which, according to the author's opinion, the science up-to-now has not given a total clear and satisfactory answer. These questions are the following:

1. What is supersaturated steam and why does it come to supersaturation of the steam?

2. Why does it come to subcooling of the supersaturated steam?

3. Why does it come to appearance of the pressure and temperature rise in the Laval nozzles, when slightly superheated, saturated and wet steam expands in them?

4. Why does that pressure rise displace along the axis of the nozzle, toward the exit, or toward the entry, in dependence on the initial state of the steam, and why does the magnitude of the pressure rise change in dependence on that whether the starting state of the steam is superheated, saturated or wet (see the end of chapter 6.3)?

5. Why does after the appearance of pressure rise the steam begin to condense (see the blue fog in Fig. 4 and the explanation in attachment 3)?

6. Why does it come to the displacement of the Wilson lines in the *h,s*-diagram, when the entering steam is wet (see Figs. 10 and 13)?

7. Why does it come to refraction of isentropic curve of the water steam in the *p,v*-diagram at its passing from superheated to wet region (see attachment 3)?

8. How is the empirical exponent of supersaturated steam estimated (see attachment 1)?

9. How are the properties of supersaturated steam estimated in the end state of supersaturation (3) and in the end of the pressure rise (4) when the friction is not taken in consideration (see chapters 5 and 6)?

10. The author has proved experimentally that at isochoric cooling of water in a bit bigger vessel, which in principle is totally equivalent to the cooling of water in a little blinded ampoules, no metastable states nor negative absolute pressures can be reached (as it is mentioned in existing literature).

11. The author has given one physically acceptable explanation for the phenomenon of heating of droplet water in oil with the same density as the water without need for that explanation to refer to the metastable states.

12. The author has pointed out that the supersaturation of steam in the nozzles does not depend on velocity of the flow (whether Ma > 1, or Ma < 1) but only on the acceleration of fluid.

13. The author has pointed out how the nonequilibrium processes and states could be drawn and represented conditionally in the equilibrium diagrams, *p,v*, *h,s* and *T,s* (see Figs. 5, 8 and 9,… etc.).

In these 13 points the author of this work has mentioned the things for which he thinks that are new in the represent work "A Few Proofs for Nonexistence of the Metastable States".

ATTACHMENT 1
DISCUSSION FOR THE ISENTROPICS EXPONENTS k' AND k OF THE WATER STEAM

In the up to now literature (Ref. [2], [3], [5], [6], [8], etc.), the numeric value for the exponent of the supersaturated steam k' is adopted equal to the value of the isentropic exponent of the superheated steam $k = 1.3$, considered as ideal gas. According to that, up-to-now the values $k' = k = 1.3$ are adopted. However, these adoptions are very erroneous, which could be seen from the real values of the true specific heats c_p and c_y for water steam given in Ref. [4], pages 440 and 441. From the ratio of these specific heats, $c_p/c_v = k$, which is calculated for some pressures, e.g., for pressures 1 kp/cm^2 and 5 kp/cm^2, it can be seen that this ratio shows noticeable discrepancy from the up to now adopted value 1.3, and so much more, as the state of the steam is nearer to the curve of saturation, $x = 1$. This is still clearly seen from the curve of the exponent of the superheated steam $k = f(p, t)$ in Fig. 20, which is drawn on the basis data for c_p and

c_y from Ref. [4], for pressure 1 kp/cm^2 ≈ 1 bar. From this curve it can be seen that the up to now adopted value 1.3 could be used with satisfying exactness only for high superheated steam, but not for superheated steam in vicinity of the curve of saturation, $x = 1$, and exceptionally not for the supersaturated steam whose (nonequilibrium) states are found under the curve of saturation, $x = 1$, see the extrapolated (dashed) curve of the supersaturated steam $k' = f(p, t)$ in Fig. 20.

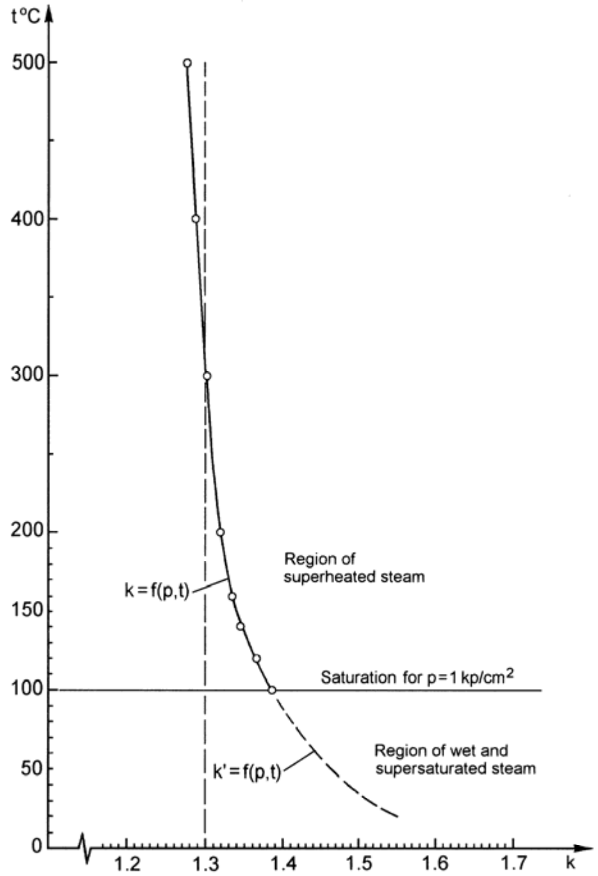


Fig. 20. Graphical presentation of the ratio $k = c_p / c_v = f(p, t)$ obtained on the basis of data for true specific heat capacity c_p and c_v for water steam. (Taken from [4].) The part $k' = c_p / c_v = f(p, t)$ is the extrapolated part of the curve $k = f(p, t)$ from superheated to the wet region.

On the basis of the proof shown in Fig. 20, the author of this work has adopted, at the numeric calculations in his work, as much more exact value for the exponent of the supersaturated steam that value for k' which is obtained with dividing of the true specific heats c_p and c_v for saturated steam in the given case. For example, if the pressure in the state A (see Fig. 2), when the supersaturation starts, is 1 kp/cm^2≈ 1 bar, then the exponent of the supersaturated steam must be the least $k' = 1.385$ (see Fig. 20) and as it is seen it is much bigger than the up-to-now adopted value $k' = k = 1.3$, as for ideal gas. These new values for k' have given an excellent result at the numeric calculation in this work (see, for example, one such solution shown in attachment 4).

ATTACHMENT 2
WILSON LINES AND WILSON ZONE FOR DIFFERENT TYPES OF NOZZLES

In Fig. 21 8 types of nozzles are represented with which the experiments of Stepanchuk, Saltanov and Ciklauri were done, mentioned in the literature [2] of this work. The measured data for every of these 8 nozzles are shown in Fig. 22. So, for example, the measured data for the nozzle N^0 5 from Fig. 21 are marked in Fig. 22 with the sign Δ. Their measuring represents the start and the end of the expansion process up to the pre-appearance of the little pressure rise (see the magnitude H_0), for different starting superheating of the steam at the same pressure, as, for example, for the pressure 2 bar for the nozzle N^0 5. The end states of these expansion processes lie on the same end line in the *h,s*-diagram that is called Wilson line. The line is not drawn in Fig. 22 but for the nozzle N^0 5 it lies a bit over the curve with constant dryness $x = 0.96$ kg/kg (see the end states Δ a bit over the curve). For each of these 8 nozzles shown in Fig. 21 can be drawn one particular Wilson line. All Wilson lines together lie in the region between the dryness $x = 0.96$ and $\underline{x} = 0.93$ (see Fig. 22). This region is called **Wilson zone**. It comes that every expansion of superheated, saturated or wet steam regardless of the starting state and the type of the nozzle finished in the Wilson zone.

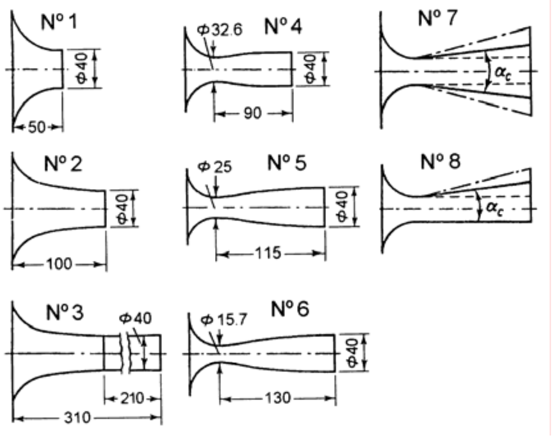


Fig. 21. Convergent and Laval nozzles with which the experiments of Stepanchuk, Saltanov and Ciklauri are done. (Taken from [2].)

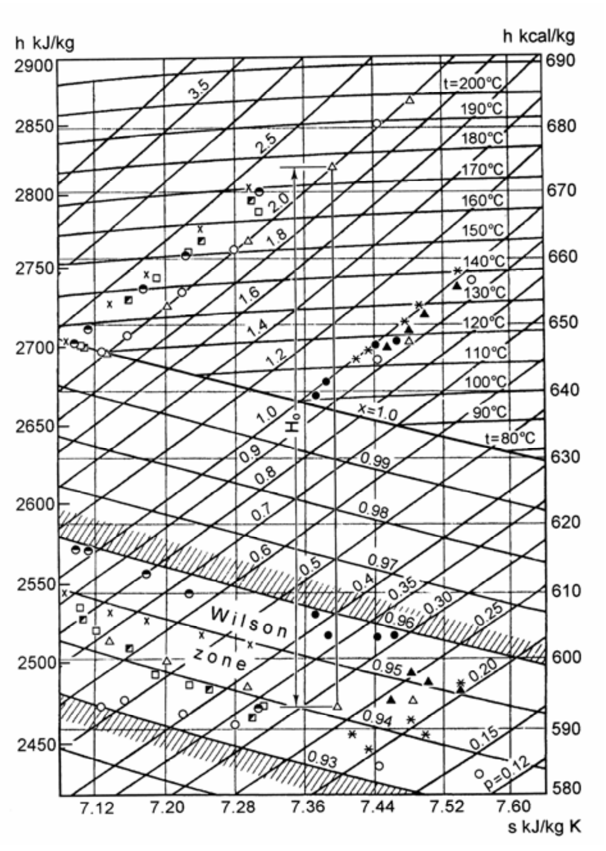


Fig. 22. Defining the position of the Wilson zone in *h,s*-diagram on the basis of the experiments made with the nozzles in Fig. 21. The symbols H, H, O,…,in this figure represent the start and the end of the expansion process up to the pre-appearance of the little pressure rise (see the magnitude H_0) for the used nozzles from Fig. 21, where symbols are: H-nozzle N°1, H-nozzle N°2, O-nozzle N°3, X-nozzle N°4, Δ-nozzle N°5, O-nozzle N°6, O-nozzle N°7, Δ-nozzle N°8. (Taken from [2].)

ATTACHMENT 3

PHYSICAL EXPLANATION OF THE PROCESS OF ISENTROPIC EXPANSION OF WET WATER STEAM

The key for revealing and solving the previously discussed problems about the supersaturated steam, the author of this work has found in the physical interpretation and explanation of the discontinuity (refraction) of the isentropic curve in the *p,v*-diagram, which appears on the limit curve of the saturated steam $x = 1$, at the crossing of the isentropic process from the superheated one to the wet region.

As an example for this explanation, we shall consider one isentropic expansion process of water steam 1-A-2 (Fig. 23), which extends from superheated to wet region. For this case we shall imagine that the steam which expands is situated in one adiabatic isolated cylinder with a movable piston, which via a geared level *L* and the gear *Z*, is in yoke with a profiled plane π and the weight *m* in order to be realized for the whole time of the proceeding of the process total internal and simultaneous external equilibrium of the steam with the surrounding. The plane π is profiled so that the changeable force which is produced by the pressure of the steam $p = f(v)$ from the inside of the piston is at any moment equal to the forces with which from the opposite side of the piston the atmospheric pressure p_0 and the force from the changeable moment $M = l\,m$ which is produced by the weight *m* via the rope and the plane π act. At this consideration the friction is everywhere neglected, and it is imagined that the process 1-A-2 proceeds so much slowly as it is necessary for it to flow in equilibrium and reversibly, namely as an isentropic process.

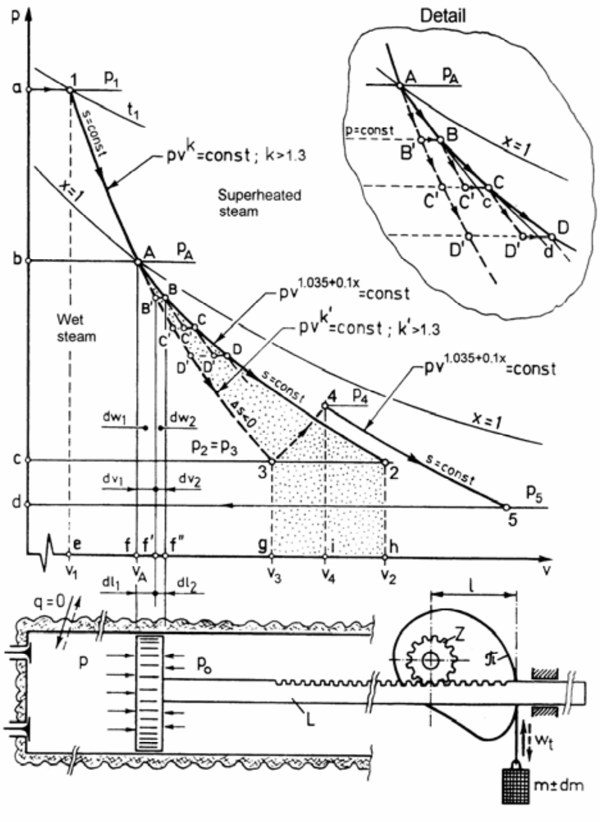


Fig. 23. Proceeding of reversible isentropic process of water steam 1-A-2 in cylinder with a movable piston. Because of comparison the corresponding nonequilibrium process 1-A-3-4-5 which should proceed in the Laval nozzle with supersaturation A-3 and the pressure rise 3-4 of the steam is drawn

The starting of the process in one or opposite direction proceeds with adding or taking away of the elementary small mass $+dm$ or $-dm$ from the weight *m* (Fig. 23). If to the weight *m*, the elementary mass +*dm* is added, it will come to the elementary small nonequilibrium between the steam in the cylinder and the surrounding bodies; therefore the weight will start lowering and via the system of mechanism will start equilibrium to compress the steam in the cylinder. At the taking away of the elementary small mass −*dm*, the steam will start expanding, will do work and will start lifting the weight. When the elementary mass ±*dm* is not added nor taken away the system will be in equilibrium, so there will have neither expansion nor by compression. Accordingly, by adding or taking away of the elementary small mass ±*dm* the process is thrown away of the equilibrium state and it can be directed in one or the opposite direction or to stop totally at any given moment during the proceeding of the process.

From the Fig. 23 it can be seen that the considered isentropic process 1-A-2, will proceed at different values of the exponent, as it follows: for all time while the steam is superheated, from states 1 to A, the expansion will proceed with continuous increasing exponent $k > 1.3$, while after that, in the wet region, from state A to 2, the expansion will proceed with smaller and continuous decreasing exponent $k = 1.035 + 0.1x$. From Fig. 23 it is seen in the state A, where the isentropic process 1-A-2 crosses the limit curve of the saturated steam $x = 1$, comes to one noticeable discontinuity (refraction) of the isentropic curve, because the part of the process 1-A proceeds with exponent $k > 1.3$, while the part A-2 with smaller exponent, $k = 1.035+0.1x$.

Such proceeding of the process implies the following important question: Why does the isentropic process not go on to proceed continuously in the wet region, too, according to the curve 1-A-3 (Fig. 23), but from the state A to 2 proceeds with smaller exponent and due to that makes the mentioned discontinuity.

In the literature that was at disposal to the author, he could not find a physical interpretation for this phenomenon, which has a fundamental significance at revealing the mysteries of the supersaturated steam, and the same has been explained by him as it is presented below.

The part of the isentropic process 1-A, which proceeds in the superheated region, with exponent $k > 1.3$, is not very interesting for discussion, because for it the same explanations are valid for reversibility as for any other process which proceeds with a gaseous body as an isentropic process, at $q = 0$ and $s = \text{const}$. However, the second part of the process A-2, which will be the subject of further discussion, is interesting because in that part the isentropic process changes its exponent from $k > 1.3$ to smaller value of *k*, which, according to the empirical formula of Zeüner (1840), is equal to the term:

$$k = 1.035 + 0.1x\,, \qquad \text{(a)}$$

where *x* is the dryness of the steam in kg/kg. This formula is applicable for the pressures to around 20 bar in the region of dryness between $0.7 \le x \le 1.0$. For saturated steam, at $x = 1.0$, the relation (a) passed in the value:

$$k = 1.135. \qquad \text{(b)}$$

In order to understand exactly how the equilibrium isentropic process A-2 proceeds, we shall divide it to numberless elementary small parts beginning from the starting state A, which lies on the limit curve of saturation $x = 1$ (Fig. 23). In that state the properties of the saturated steam are: p_A, T_A and v_A. Now we will suppose that the steam, starting from the state A up to the achievement of some very close state B', will do some elementary small expansion process A-B', therefore the volume of the steam will increase for dv_1, the piston will move for a distance dl_1, and the steam will do some elementary small absolute work dw_1, equal to the area A-B'- f '-f-A (Fig. 23). Due to that it will come to elementary decrease of the internal energy of steam (decrease of the kinetic energy of the molecules) for du_1 followed with elementary fall of the pressure and the temperature of the steam for *dp* and *dT*.

Due to this elementary expansion and cooling of the steam, it will come to condensation of one part of it, and from that part, at once after the crossing of the limit state A, it will start to form certain amount condensate, with mutual sticking of the closest and slowest molecules, while the rest (noncondensed) gaseous phase of the steam will behave further on as a pure gas and will go on to expand from state A to B' with continuous increasing exponent $k' > 1.3$, as the superheated steam in the part of the process 1-A (Fig. 23). Due to that the properties of the gas phase of the steam in the new close state B' will be: $p_{B'} < p_A$, $T_{B'} < T_A$ and $v_{B'} > v_A$. However, the condensate, which has been formed during the elementary expansion process A-B', could, at the proceeding of this expansion process, neither expand nor do work as the gaseous part of the expanding steam, because the liquids are practically nonexpanding and noncompesible.

Therefore, the temperature of the condensate in the new state B' will stay somewhere in the middle between the temperatures T_A and $T_\mathrm{B'}$ at which it is formed. This middle temperature will be marked with $T_\mathrm{A\text{-}B'}$.

In this manner, in the new state B', a mechanical (nonequilibrium) mixture of steam in pure gaseous state, with properties $p_\mathrm{B'}$, $T_\mathrm{B'}$ and $v_\mathrm{B'}$, will become and condensate with higher temperature $T_\mathrm{A\text{-}B'} > T_\mathrm{B'}$. Due to the difference in temperatures it will come to isobaric evaporation of a part from the condensate, therefore the volume of the steam will increase for dv_2, the piston will move still for the way dl_2 and the steam will do an adding elementary absolute work dw_2, equal to the area B'-B-f "-f '-B' (see Fig. 23). This little isobaric expansion process will last until the equalization of the temperatures of the liquid and the gaseous phase, which will be achieved in the state B at achieving the same temperature T_B and the same pressure p_B of both phases.

The elementary small processes A-B' and B'-B, are both adiabatic processes because they proceed without an exchange of heat with the surrounding, but at the same time they are also nonequilibrium processes because they proceed at existing of the elementary small difference in temperatures dT between the condensate and the gaseous phase of the steam until the achievement of the new equilibrium state of the wet steam B. However in reality the elementary processes A-B' and B'-B do not proceed one after another as it was previously described, but simultaneously so that their resultant process is represented with the elementary small isentropic process A-B (Fig. 23), which at starting dryness $x = 1$ proceeds, see Eq. (a), at exponent:

$$k_B = 1.035 + 0.1x_B < k_A = 1.135. \qquad \text{(c)}$$

Now we shall consider what will happen if the previously considered elementary small isentropic expansion process A-B is extended with a second also elementary small expansion process whose start is in state B. Due to this second elementary small expansion process the gas phase of the steam will do an elementary absolute work, equal to the area under the elementary process B-C'. This elementary work is acting at the expense of decreasing the internal energy of the gaseous phase of the steam that is followed with elementary fall of its pressure and temperature for dp and dT. Due to that condensation of one more elementary part from the gaseous phase of the steam will happen, and from it, at once after the passing of the state B, besides the old condensate, it will start to form a certain amount of new additional condensate (liquid), while the rest gaseous phase of the steam which has stayed noncondensed during this second elementary expansion, will behave as a pure gas and will go on to expand from state B to C', again with exponent $k' > 1.3$, and its properties in the new state C' will be: $p_\mathrm{C'} < p_\mathrm{B}$, $T_\mathrm{C'} < T_\mathrm{B}$ and $v_\mathrm{C'} > v_\mathrm{B}$. At the same time, the total amount of the old and new condensate will stay again at some higher middle temperature $T_\mathrm{B\text{-}C'}$ in relation to the achieved temperature $T_\mathrm{C'}$ of the gaseous phase in the state C'. Due to the difference in temperatures $T_\mathrm{B\text{-}C'} > T_\mathrm{C'}$, it will come again to isobaric evaporation of a part from the condensate, therefore the steam will do still an additional elementary absolute work, equal to the area under the elementary isobaric process C'-C. This isobaric evaporation will last until the equalization of the temperatures of the liquid and gaseous phase of the steam that will be achieved in the new equilibrium state C, at achievement of the same temperature T_C and the same pressure p_C of both phases. As it was previously said, the elementary small and nonequilibrium adiabatic processes B-C' and C'-C proceed simultaneously therefore their resultant process is represented with the elementary small isentropic process B-C (Fig. 23), whose exponent is:

$$k_C = 1.035 + 0.1x_C < k_B < k_A = 1.135. \qquad \text{(d)}$$

The exponent k_C is smaller than k_B because the dryness of the steam in the state C is smaller than that in B, $x_\mathrm{C} < x_\mathrm{B}$. It means that the total amount of equilibrium liquid in state C is bigger than that in B. Therefore, at the equalization of the properties of state of the gaseous part of the steam and the liquid (condensate) at the elementary small isobaric processes B'-B and C'-C, the length of the isobaric process C'-C will be bigger than the length B'-B, because the bigger amount of liquid in the state C' evaporates in smaller amount gaseous steam with state C', and so the new state of the equilibrium mixture will not lie in the extension B-c of the direction of the elementary small process A-B, but a bit further on in the state C (see details in Fig. 23), therefore $k_C < k_B$.

If a third elementary small expansion process is considered starting in the state C, in the previously described manner, the elementary small nonequilibrium adiabatic processes C-D' and D'-D will proceed whose resultant isentropic process C-D will proceed with a still smaller exponent:

$$k_D = 1.035+0.1x_D < k_C < k_B < k_A = 1.135,\text{...etc.} \qquad \text{(e)}$$

In this manner, through one endless chain of elementary small nonequilibrium processes A-B'-B, B-C'-C, C-D'-D,…,etc, which proceed at an endless small internal nonequilibrium, a continuous equilibrium isentropic expansion process of the wet steam A-B-C-D- ... -2 is being done which, as we have seen, proceeds at the changeable exponent *k*, which decreases continuously as the dryness of the steam is decreasing during the expansion. It is clear that the total equilibrium between the gaseous phase of the steam and the formed liquid condensate can be achieved only in the states B, C, D,…, 2, which form the continuously isentropic curve of the wet steam A-2 (Fig. 23).

Relaxation time

In order to pass over the elementary small nonequilibrium processes A-B'-B, B-C'-C, C-D'-D,…, to the equilibrium states B, C, D,..., 2, which lie on the isentropic curve A-2, the process A-2 must proceed so long as it is necessary for sticking of the slower molecules of the gaseous phase of the steam and the formation of the nonequilibrium amount condensate (or nonequilibrium droplets condensate) at the elementary small nonequilibrium adiabatic expansion processes A-B', B-C', C-D',…, after that for its partial evaporation at the elementary small nonequilibrium isobaric processes, B'-B, C'-C, D'-D,..., up to the final formation of equilibrium condensate (or equilibrium droplets condensate) in the isentropic states B, C, D,..., 2. That time which is necessary for successive restoring of each next equilibrium state is called **relaxation time**. That time is necessary for equilibrium redistribution of the mass and energy and achievement of equal pressure and equal temperature in each elementary part of the fluid at each elementary passing of the fluid from one equilibrium state to another.

When the fluid is only liquid, or only gaseous, as, for example, at the part of the process 1-A (Fig. 23) which proceeds in the superheated region, then the time necessary for relaxation of the process is insignificantly small, because it is equal to the time that is necessary for flight and crash of some molecules with others. However, when during the proceeding of the process the fluid changes its aggregate state, as, for example, at the part of the process A-2 (Fig. 23), when the fluid passes from a gaseous to liquid phase, then the relaxation time is much bigger in relation to the previous case, because each new equilibrium state is achieved through proceeding of more nonequilibrium intercrosses – the elementary small processes A-B'-B, B-C'-C, etc. According to that, when the time of proceeding of some process is longer than the relaxation time, then the process with safety will proceed in equilibrium, as it is the case with the described isentropic process A-2 in Fig.23.

But if the time of proceeding of the process is shorter than the necessary relaxation time, as it is, for example, the case at the extreme rapid expansion processes of water steam in the convergent and Laval nozzles, then the process will flow in nonequilibrium and with appearance of the previously discussed phenomena of supersaturation and subcooling of the steam. Such a process will proceed in nonequilibrium because there is not enough time for formation of bigger and equilibrium droplets condensate consisted of few hundreds molecules, or equilibrium condensate as at the process A-2 in Fig. 23, but there is time only for formation of extreme small particles condensate, consisted of two, three or only few molecules, which, due to the extreme speed of proceeding of the process, do not succeed in getting in touch neither mutually nor with the rest of the gaseous phase of the steam, and therefore stay in internal nonequilibrium with the gaseous phase of the steam which goes on to expand and to cool.

In this case all elementary small nonequilibrium adiabatic processes A-B', B-C', C-D',..., instead of being parts of isentropic zig-zag curve A-2, they will extend one after another until the achievement of the end nonequilibrium state 3 and in that manner they will form the nonequilibrium adiabatic process A-3, which will proceed with supersaturation and subcooling of the steam. That can be seen more clearly from the details in Fig. 23, where the elementary small nonequilibrium adiabatic processes A-B', B-C', C-D',..., which are parts of the equilibrium zig-zag curve A-2, in fact are equal to the parts A-B', B-C', C-D',..., which form the nonequilibrium adiabatic curve A-3. They are only an equidistancly displacement to left along the isobars p = const.

From the same detail it can also be seen that at the process A-3, in relation to the process A-2, the elementary small nonequilibrium isobaric processes B'-B, C'-C, D'-D,..., are missing at which partial evaporation of the condensate at the isentropic process A-2 is performed. Because at the process A-3 it does not come to evaporation of the small particles condensate and the internal energy which they can free at their eventual evaporation will stay enslaved (accumulated) in them. That enslaved energy is equal to the dotted area A-2-h-g-

3-A , see Fig. 23 and Eq. (1), which show us for what amount the nonequilibrium process A-3 gives less absolute work in relation to an eventual isentropic process A-2, which would proceed from the same initial state A to the same pressure $p_2 = p_3$.

If from any cause comes to breaking (evaporating, or exploding) of the small nonequilibrium particles condensate with start in state 3, it will come to freeing of the enslaved internal energy in them, due to that it will come to appearance of the little pressure rise 3-4 (Fig. 23) as at the Laval nozzles, after which the new equilibrium state 4 will restore. From the state 4 up to the exit state 5 (Fig. 23) the process will go on to proceed in equilibrium and forming of bigger and equilibrium droplets condensate, see the blue fog in Fig. 4, etc. and etc.

ATTACHMENT 4
EVALUATION OF THE END STATE OF SUPERSATURATED STEAM IN EQUILIBRIUM *h,s*-DIAGRAM

Figure 24 shows a numeric example of evaluating the end state of the supersaturating process A-3 in real *i,s*-diagram. In this case the starting state of the steam A is saturated from p_A = 1.2504 bar. The end state 3 of that process is found in the intersect of the next nonequilibrium extensions: $v_2 = 2.6215$ m^3/kg, $p_{2'}$ = 0.5127 bar and $t_{3'}$ = 23.5°C. This solution of this process is the same in Fig. 8. The state 2 represents the end state of the comparable isentropic process A-2 [7].

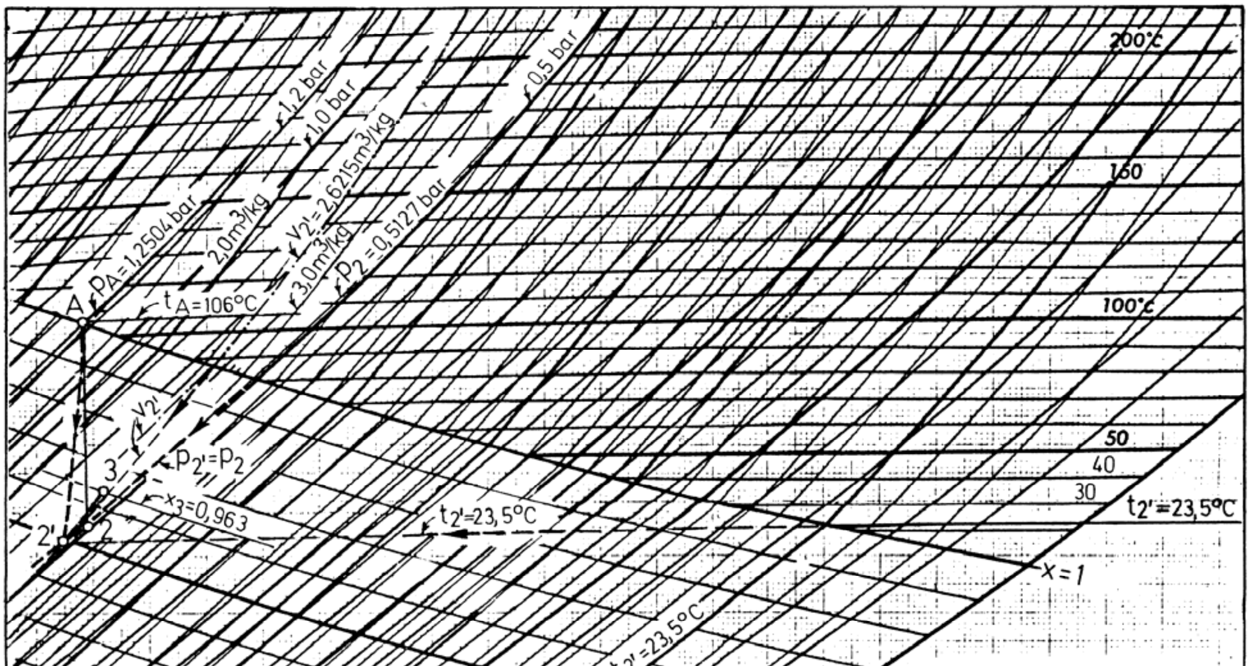


Fig. 24. Evaluating the end state of the supersaturated steam 3 in the real *h,s*-diagram in the intersect of the nonequilibrium extensions: $v_{2'}$ = 2.6215 m^3/kg, $p_{2'}$ = 0.5127 bar and $t_{3'}$ = 23.5 °C of one numeric example. The state 2 is the end state of the isentropic process A-2. This solution is the same as it is shown in Fig. 8.

REFERENCES

[1] F. Boshnjakovich: *Science for the Heat*, Fourth edition, Zagreb, 1970.

[2] M. E. Dach, G. A. Philipov: *Gasdynamics of Two-phase Mediums*, Energy, Moscow (1968).

[3] V. M. Faires: *Thermodynamics*, Fourth edition, The Macmillan Company, New York, 1962.

[4] D. L. Malich: *Thermodynamics and Thermotechnics*, Fourth edition, Gradjevinska knjiga, Belgrade, 1967.

[5] E. F. Obert, R. A. Gaggioli: *Thermodynamics*, Second edition, Mc Grow-Hill Book Company, inc. New York, San Francisco, Toronto, London, 1963.

[6] M. Opreshnik: *Thermodynamics*, Ljubljana, 1974.

[7] K. Raznjevich: *Mollier's h,s-diagram for Water Steam to 1000°C and 950 b*ar, according the Data by M. P. Vucalovich, Zagreb, 1981.

[8] J. T. Rettaliata: Undercooling in Steam Nozzles, *Trans. ASME*, **58** (11), p. 599–605 (November) 1936.

[9] M. P. Vukalovich, I. I. Novikov, *Equations of State of the Real Gases*, Moskow – Leningrad, 1948.

[10] M. P. Vukalovich, S. L. Rifkin, A. A. Aleksandrov: *Tables for Heatphysical Features of Water and Water Steam*, Moscow, 1969.

[11] M. P. Vukalovich: *t,s-Diagram for Water Steam to 1000°C and 950 bar,* Mashgiz, Moskow.

[12] A. Stodola: *Steam and Gas Turbines*, New York, 1927.

[13] J. I. Yellot, Supersaturated Steam, *Trans. ASME*, **56** (6), p. 411–430 (June) 1934.

[14] J. I. Yellot, C. H. Holland: Condensation of Steam in Diverging Nozzles, *Trans. ASME*, **59** (3), p. 171–183 (April) 1937.

Резиме

НЕКОЛКУ ДОКАЗИ ЗА НЕПОСТОЕЊЕ МЕТАСТАБИЛНИТЕ СОСТОЈБИ

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Клучни зборови: презаситена пареа; метастабилни состојби; нерамнотежна влажна пареа; мали нерамнотежни честички кондензат; мал притисен кондензационен скок; рамнотежни капки кондензат

Оваа статија претставува поголем дел од еден досега необјавен труд на авторот, чиј наслов е “Неколку докази за непостоење на метастабилни состојби”. Поради големиот обем на трудот, тука ќе бидат дискутирани главно проблемите на презаситената (метастабилна) пареа која се јавува при струењето на незначително прегреана, заситена или влажна пареа во конвергентните и Лаваловите млазници. Оваа пареа се наведува во литературата како еден од најцврстите докази за постоење метастабилни состојби кај супстанциите. Во овој труд за таа пареа е најдено дека таа не е еднофазна гасна метастабилна пареа, како што се мислело досега, туку дека таа е нерамнотежна влажна пареа во која за време на експанзиониот процес во млазниците се формираат екстремно мали честички кондензат, составени од две, три или само неколку натрупани молекули, кои остануваат во топлинска, механичка и внатрешна нерамнотежа со другата експандирачка гасна фаза на пареата. Тоа значи дека оваа пареа, која е наречена презаситена или метастабилна, всушност не постои бидејќи, таа не е ништо друго туку само нерамнотежна влажна пареа која е составена од две фази: од експандирачката гасна фаза на пареата во млазникот и спомнатите мали и нерамнотежни честички кондензат кои се формираат во неа.

Новите теоретски објаснувања презентирани во овој труд даваат можност не само за едно целосно физичко сфаќање на суштината на презаситената пареа, туку даваат можност и за одредување на величините на состојба на таа пареа на крајот на презаситувањето кое се случува при постигнувањето на Вилсоновата линија во h,s-дијаграм. Во статијата исто така се објаснети и причинте поради кои доаѓа до појавата на изненаден мал притисен кондензационен скок, кој се случува редовно во Лаваловите млазници веднаш по крајот на презаситувањето на пареата во нив, односно веднаш по постигнувањето на Вилсоновата линија во h,s-дијаграм. Тука е даден и начинот на пресметка на величините на состојба на пареата на крајот на скокот. По тој скок пареата продолжува да експандира рамнотежно и со формирање на поголеми и рамнотежни капки кондензат сѐ до излезниот пресек на млазникот. Ако млазникот е стаклен, овие капки кондензат можат да се видат со очи како сина магла. После скокот експанзиониот процес во млазникот се одвива стандардно и како таков не е интересен за понатамошни разгледувања.

Во оваа статија се дискутирани накусо и други примери за постоење метастабилни состојби кај супстанциите, цитирани во постојната литература, како што е, на пример, случајот на ладење на вода во мали затворени стаклени ампули кое го вршел Бертолд. Со овој експеримент исто така е укажано и на можноста за постигање негативни апсолутни притисоци кај супстанциите, што е многу неверојано и невозможно (??). Како опозиција на овој пример, авторот на овој труд направи експерименти со изохорно ладење на незаситена чиста вода од 1 bar сместена во поголем стаклен сад и најде дека во овој случај не се појавија ниту метастабилни состојби ниту негативни апсолутни притисоци. Како уште еден пример за постоење метастабилни состојби, во литераурата се наведува и случајот на греење на капки вода потопени во масло (со иста густина како водата), кои не испарувале сѐ до температра од 180°C, иако притисокот (на маслото и капките) бил приближно еднаков на атмосферскиот притисок, итн.

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MATHEMATICAL DETERMINATION OF SYNTHETIC SURFACE'S PERPENDICULAR AND TANGENT LINES

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Abstract: In this paper, a geometric and a mathematical model with computer algorithm of perpendicular and tangent lines of the synthetic surfaces, composed of splines in two directions, are presented. Synthetic surfaces are used in an engineering design for describing parts with aerodynamic or other functional and esthetic shapes. Synthetic surfaces can be represented by the majority of contemporary CAD systems. The modern NC machines contain highly sophisticated controllers and processing tools, which provide complex synthetic surfaces manufacturing. During the machining process, machining tool's axis has to be placed perpendicularly to each point of the synthetic surface that is the product of machining. A mathematical model is necessary for determination of the tool's position during the machining process .

Key words: synthetic surface; spline

1. INTRODUCTION

In order to perform mechanical parts with perfect and complex geometric shapes modern the computer science applies so called synthetic surfaces. Synthetic surfaces are three dimensional surfaces presented as a synthesis of several synthetic curves in two directions, characterized with smooth curve – linear shape, such as synthetic surfaces constructed of spline curves in two directions [1]. The synthetic surface can be presented with a simple parametric expression [2].

The parametric expression of the synthetic surface is explained with continual functions with two parameters: *t* and *u*, that can be changed from minimum to maximum value. Changing the values of the *t* and *u* parameters causes a definition of different curve's points. That means that *t* and *u* are acting like local parametric coordinates of the synthetic surface's points. Parameters *t* and *u* are changing in the interval of 0 to 1. The parametric expression of the synthetic surface is:

$$P(t,u) = \left[xyz\right]^T = \left[x(t,u)\,y(t,u)\,z(t,u)\right]^T ,$$

where $0 \le u \le 1$ and $0 \le t \le 1$,
or the summary of the net of control points in the perpendicular and parallel directions:

$$P(t,u) = \sum_{i=0}^{n} \sum_{j=0}^{m} \left[x_{[i][j]}(t,u)\, y_{[i][j]}(t,u)\, z_{[i][j]}(t,u)\right].$$

Neighboring control points are connected with spline curves in two directions:

$$f_{(xy)}(t) = \sum_{i=0}^{n} \left[x_{[i]}(t)\, y_{[i]}(t)\, z_{[i]}(t)\right]$$

$$f_{(xz)}(u) = \sum_{j=0}^{m} \left[x_{[j]}(u)\, y_{[j]}(u)\, z_{[j]}(u)\right]$$

Spline curves are determined with points obtained through the next mathematical expressions, that depend on *t* and *u* parameters:

$$\begin{aligned} x &= x_0 B_0(t) + x_1 B_1(t) + x_2 B_2(t) + x_3 B_3(t) \\ y &= y_0 B_0(t) + y_1 B_1(t) + y_2 B_2(t) + y_3 B_3(t) \\ z &= z_0 B_0(t) + z_1 B_1(t) + z_2 B_2(t) + z_3 B_3(t) \end{aligned}$$

where

x, *y*, *z* – coordinates of the points

$B_0(t)$ – blending function

t – parameter

The number of added points depends on the type of the applied curve, more precisely it depends on the function of the surface's control points connection. Depending on the connection function, there are several kinds of spline curves: *B-spline, Cubic B-spline, Bezier* etc.

2. MATHEMATICAL EXPRESSIONS FOR THE TANGENT AND PERPENDICULAR LINES OF THE SYNTHETIC SURFACE

The synthetic surface is bounded with parts of spline curves, defined with the values of the parameters: $t = 0$, $t = 1$, $u = 0$ and $u = 1$ (Fig. 1).

The synthetic surface could be defined as a set of points through which the spline is passing [3]. There are also determined border values for the points. For the four-edged polygon, the border values are determined with 16 vectors and 4 spline curves, four position vectors for the points $P(0,0)$, $P(0,1)$, $P(1,0)$, $P(1,1)$, eight tangent vectors (two for each point) and four vectors of curvature (one for each point).

For the different operations and applications with synthetic surfaces, it is necessary to calculate the tangent line (T_t and T_u), the perpendicular line (N) and the curvature (Z) for the determined points.

The tangent lines for a point of a surface are determined as tangents of parametric curves that are passing through that point. The parametric expression for the curve is obtained from the general equation $P(t,u)$, for $t = t_i$, and the other for $u = u_j$, which means that t_i and u_j are the parametric coordinates of the surface's points (Fig. 1). The tangent lines T_u and T_t are determined with the first extract of both the curves in an accidental point. The surface perpendicular line is determined as a vector product of both the tangent lines in an accidental point. The surface curvature Z in an accidental point is determined as a double extract of t and u.

If a surface is presented as a function of $f(x,y,z) = 0$, then the equation of the tangent surface in the point $M(x,y,z)$ is:

$$(X - x)\frac{\partial f}{\partial x} + (Y - y)\frac{\partial f}{\partial y} + (Z - z)\frac{\partial f}{\partial z} = 0 .$$

A line perpendicular (perpendicular) to the tangent surface in the point M is a perpendicular line of the surface:

$$\frac{X - x}{\frac{\partial f}{\partial x}} = \frac{Y - y}{\frac{\partial f}{\partial y}} = \frac{Z - z}{\frac{\partial f}{\partial z}} .$$

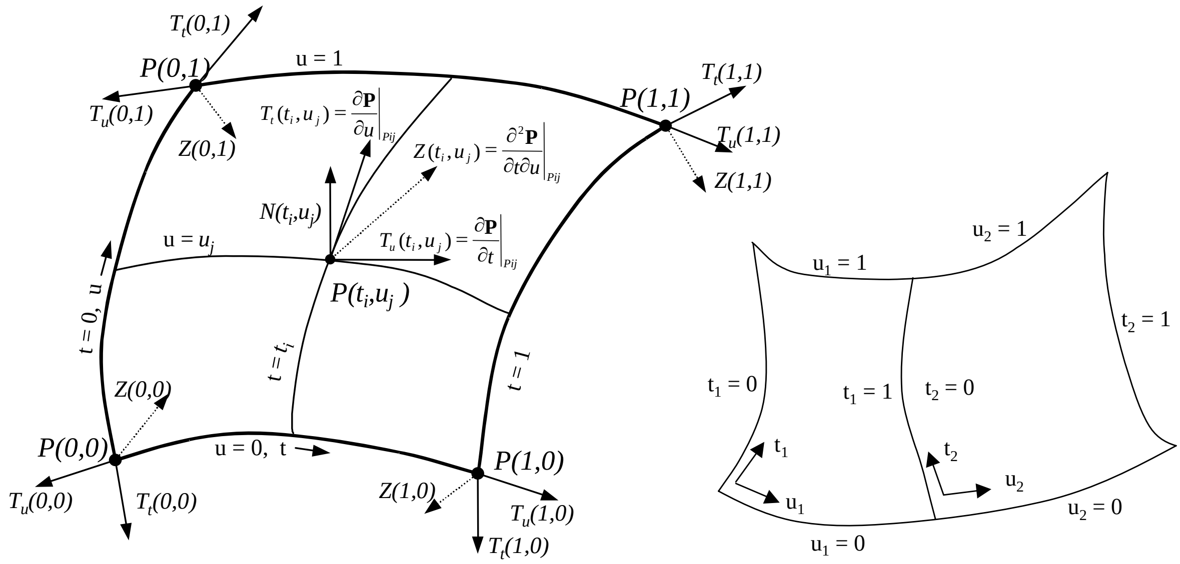

Fig. 1. Synthetic surface bounded with 4 spline curves and two connected synthetic surfaces

3. COMPUTER ALGORITHM FOR DETERMINATION OF THE SYNTHETIC SURFACE IS TANGENT AND PERPENDICULAR LINES

The problem of NC machine tool positioning perpendicularly to the surface is more complicated because the designed surface is not always a synthetic surface, nor a geometric function. The computer algorithm for providing a tangent line and a perpendicular line has to involve all possible variants of designed surfaces, and it has to be universal. Also, it has to work with imported surfaces, created in any graphical package [4].

An analysis of a synthetic surface has been made. The surface is created using synthesis of *Cubic B-spline* curves in two directions. The first spline curve $f_{(xy)}$ lays in the *xy* plane and moves along the other spline curve $f_{(xz)}$ that lays in the *xz* plane (Fig. 2).

The geometric algorithm for determination of tangent and perpendicular lines in a determined synthetic surface consists of several operations:

– section of synthetic surface with *yz* plane,

– construction of tangent and perpendicular lines of the obtained section curve $f_{(yz)}$,

– section of synthetic surface with *xz* plane,

– construction of tangent and perpendicular lines of the obtained section curve $f_{(xz)}$ (Fig. 3),

– construction of synthetic surface perpendicular line (Fig. 4).

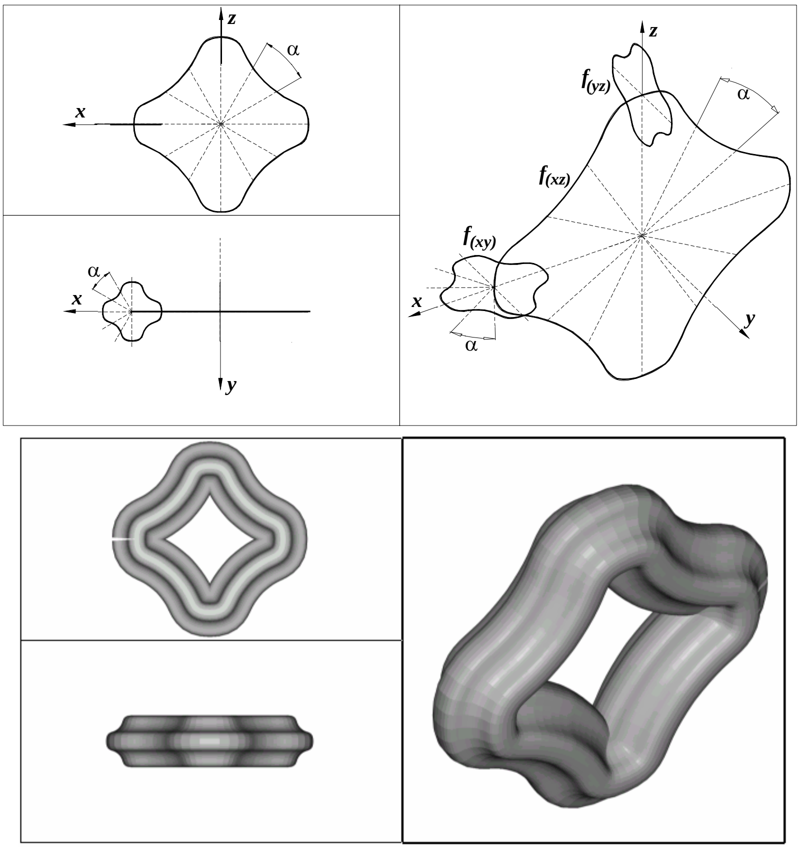

Fig. 2. Synthetic surface designed from Cubic B-spline curves $f_{(xy)}$ and $f_{(xz)}$

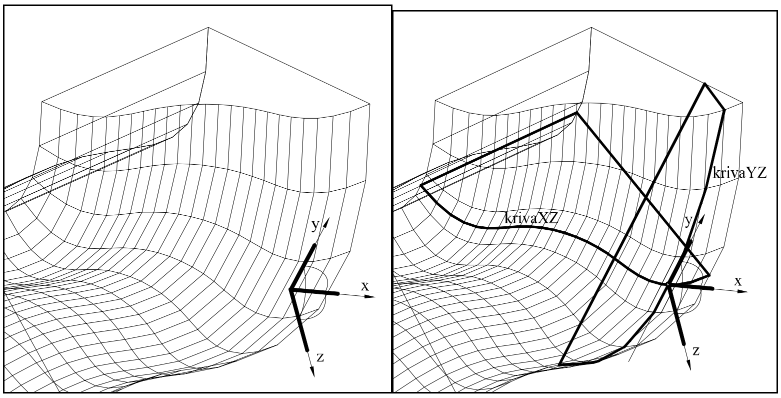

Fig. 3. Cutting curves $f_{(xz)}$ and $f_{(yz)}$ of a synthetic surface

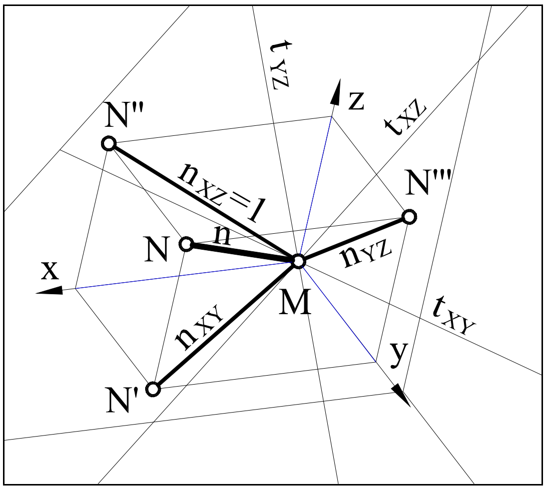

Fig. 4. Construction of a synthetic surface perpendicular line in the M point

The computer algorithm has the same structure as the geometric one, which is consisted of the same operations. On the base of the presented algorithms, a computer program for determination of the perpendicular and tangent lines for each point of a specified surface is created. This software is created as an upgrade of a commercial graphical package, using the C++ language. The procedures of the program enable a surface created in any graphical package to be imported and necessary elements for the NC tool path generation to be determined as perpendicular and tangent lines for each point of the imported surface.

Procedure 1. Section of a synthetic surface with *yz* plane

```
ads_command     (RTSTR, "_section",
                RTENAME, Mdel,
                RTSTR, "",              <section of a surface (Mdel) with YZ plane>        RTSTR, "YZ",
                RTSTR, "",
                RTNONE);
Res = ads_entlast (CurveYZ);             <obtained section curve yZ>
ads_command     (RTSTR, "_ucs",
                RTSTR, "y",
                RTSTR, "90",            <back to User Coordinate System>
                RTSTR, "",
                RTNONE);
```

Procedure 2. Section of a synthetic surface with *xz* plane

```
ads_command     (RTSTR, "_section",
                RTENAME, Mdel,
                RTSTR, "",              <section of a surface (Mdel) with XZ plane>
                RTSTR, "XZ",
                RTSTR, "",
                RTNONE);
Res = ads_entlast (CurveXZ);            <obtained section curve XZ>
ads_command     (RTSTR, "_ucs",
                RTSTR, "x",
                RTSTR, "90",             <back to User Coordinate System>
                RTSTR, "",
                RTNONE);
```

4. CONCLUSIONS

Actuality of the presented research results from a rising necessity for the NC machining of products with complex geometry. NC machining technology uses NC programs that specify the tool path for the product's machining. The NC tool path specifies the position of the tool for each point of the product's surface. The position of the tool is different for each point of the surface and its axis has to be perpendicular to the product's surface. This research includes a computer program, created as an upgrade of a commercial graphical package, using the C++ language. This program has an ability to import a surface created in any graphical package and to compute necessary elements for the NC tool path generation: perpendicular and tangent lines for each point of the imported surface. Procedures for determination of perpendicular and tangent lines for each point of a surface are made on the base of presented geometric and computer algorithms, using simple mathematic expressions.

REFERENCES

[1] Richard H. Bartels, John C. Beatty and Brian A. Barksy: *An Introduction to Splines for Use in Computer Graphics & Geometric Modeling*, CA: Morgan Kaufmann, Los Altos, 1987.

[2] Lyle Ramshaw: *Blossoming: A Connect-the-Dots Approach to Splines.* Technical Report 19. Digital Systems Research Center, June 21, 1987.

[3] Gerald Farin: *Curves and Surfaces for CAGD.* 3rd edition. Academic Press, Boston, 1993.

[4] Jorge Stolfi: *Oriented Projective Geometry. A Framework for Geometric Computations.* Academic Press, Boston, 1991.

Резиме

МАТЕМАТИЧКО ОПРЕДЕЛУВАЊЕ НА НОРМАЛА И ТАНГЕНТА НА СИНТЕТИЧКА ПОВРШИНА

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Клучни зборови: синтетичка површина; сплајн

Во овој труд е презентиран геометриски и математички модел со компјутерски алгоритам за определување на нормала и тангента на синтетичка површина, одредена со сплајн-криви во два правца. Синтетичките површини се користат во инженерскиот дизајн за опишување делови со аеродинамичен облик или други функционални или естетски облици. Синтетичките површини можат да бидат креирани со повеќето современи CAD-системи. Современите NC машини содржат високо софистицирани контролери и алати кои овозможуваат обработка на сложени синтетички површини. За време на процесот на производство оската на алатот за обработка мора да биде поставена нормално на секоја точка од синтетичката површина која се обработува. Притоа е нопходен математички модел за одредување на позицијата на алатот за време на процесот на обработка.

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MODELING THE STUDENT'S APPLICATION PROCESS USING THE NUTSHELL APPROACH

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Absrtact: This paper describes modeling of an already existing application for the new study year (winter semester) at the Faculty of Mechanical Engineering in Skopje. The paper is based on the use of a so-called Nutshell approach that allows defining the already existing processes, their visual presentation (graphs, diagrams) and creation of scenarios for improvement of the processes (if it is necessary). The paper shows the modeling made on the basis of the implemented changes in the processes using the Nutshell approach as a technique for detecting process characteristics for how it was (as-is), how it is going to be (to-be) as well as to define the actors in the process. In the Nutshell approach different visual aids are used.

The data presented in this paper have been based on various materials from the Faculty of Mechanical Engineering, as well as the consultations made with people involved in the process of application forming.

Key words: modeling; process; Nutshell approach; swimlane diagram; changes

1. INTRODUCTION

The mobility at universities and other higher education institutions in Europe expanded in the 90's of the preceeding century, among other things due to the increased mobility of students and university teachers. The quality of universities and other higher education institutions is one of the most important factors stated in joint documents, such as the Lisbon Convention (1997), the Sorbonne Declaration (1998), the Bologna Declaration (1999), the Prague Communiqué (2001) and the Berlin Communiqué (2003), Bergen (2005) [1].

At the Berlin conference held in September 2003 the Republic of Macedonia assigned the Bologna Declaration. With this Declaration the Republic of Macedonia has committed to obtain total reconstruction of the higher education until the year 2010. The purpose of the Bologna process implementation is to achieve greater compatibility and comparability of the systems of higher education in Europe in order to make the study process more efficient and effective [3].

The same year of Declaration acceptance, the Faculty of Mechanical Engineering in Skopje started to prepare the transformation process according to the Bologna process. In October 2003 the Education and Scientific Council at the Faculty of Mechanical Engineering decided to start with the transformation process preparing term plan and electing team that would prepare a project for processes improvement and reengineering of the study programs according to the Bologna Declaration and the European Credit Transfer System. After three months and many meetings on different levels at the Faculty a project results was presented by the work group, which was adopted at the Education and Scientific Council in February 2004. In this way the Faculty finished the formal part of the process. At the Board of Rectorate meeting in March 2004 the new curriculum and syllabuses for the Faculty of Mechanical Engineering were accepted and implemented in the next 2004/05 study year [2].

New curriculum and syllabuses rised many questions for different changes at the institutional level. One of the main questions that remained unsolved by the elaborate for transformation was the student's application process for assignment of the new study year. In August 2007 a work group made en effort to make changes for this issue and a modified application process was proposed.

The processes approach is very important during the institutional transformation. This article has a purpose to model of an already existing process using the most common approach, Nutshell and diagrams not so frequently used but very efficient such as Swimlane diagrams (other names: Process map, Process responsibility diagram, Responsibility process matrix and so on). The Nutshell approach is a process for the process improvement in which various modeling techniques and frameworks are involved. The process workflow modeling is the central technique for the process [5]. This approach is useful not only for the transformation process but as a tool for reviewing already made transformation as well. It is an approach that offers continuous follow up of the processes.

2. IDENTIFICATION OF THE IMPROVEMENT PROCESS (FRAMING THE PROCESS)

The president of the Texas Instruments has had this message on his desk: *If you do not change the processes you cannot expect changes into results* [4]. People that work on the quality management are familiar with the importance of the processes reviews even when a change was made. No matter of the quality philosophy (TQM – Total Quality Management, Kaizen's, Crosby's or Juran's) the key issue for the quality is the process management. It is very important to mention that processes are different from functions. In one company/institution functions are given by default by the job but the process is the "invisible" part of the collaboration between functions or just as a part of one function. With a simple definition, the process is a particular course of actions intended to achieve a result (procedure) [5]; it is series of actions or operations conducting to an end [6]; or the process is a way for the enterprise to organize work and resources (people, equipment, information and so forth) to accomplish its aims [7]. According to these definitions it might be easy to figure out which activities are part of the process. The employees are usually those who identify processes, which is the case with the student's application at the Faculty of Mechanical Engineering in Skopje. This student's application process has three basic phases:

1. Fulfillment of an application form by the student (recommended from the Ministry of Education and Science);
2. Receiving the forms by the student service at the Faculty;
3. Issuing permission by the student service, which allows the student to attend the following year (except for the first year application).

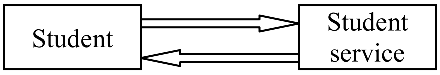

Fig. 1. Basic relation between the enablers of the application process

With this basic approach we are able to see two enablers (actors) – the student and the student service (Fig. 1). What we are not able to see is the interrelations that define the real structure of the process. This is how the real process goes. The Vice-Dean for education proposes conditions for assigning new study year (except for 1st year of study). Proposed conditions are approved by the Educational and Scientific Council of the Faculty. When conditions are approved, they are published at the information panel at the Faculty, at the web page and at the student service. The basic requirements for student application process are: number of passed exams during the previous year completion of the application forms, payments for student funds and participations, confirmation forms from the library and the time period for application. When the student has collected all signatures from his/she teachers for the attended classes from the previous year and grades for the passed exams, he/she has to pay all expenses for the Faculty in the bank (student funds and participations). Also he has to buy application forms and statistic forms that are issued by the Ministry of Education and Science. Next, when the student completed the forms, he goes to the student service desk (which works from 12 till 14 o'clock every day) during the application period with the student identification card (ID in further text) to apply for the approval to continue next year. The approval can be given for a day or a week. The process is mostly confusing for the students. The process continues within the student service. The student service currently has three employees. Their job is to open a register/file for every student (in directory book and in the computer data base). When the student passes an exam he brings a grade form to his teacher. The teacher signs the grade form and brings the grade forms to the student service. The student service collects grade forms and adds every single grade in the database and puts the grade forms into the student's file. When a student gives his application for the new study year (in September) the student service checks whether the student has fulfilled all conditions for assignment of a new study year. If it is all right the service brings the student's ID back to the student with a stamp for permission. If some problem exist the Vice-Dean for education is informed about it or the student has to pay to be allowed to attend the previous year again (Fig. 2).

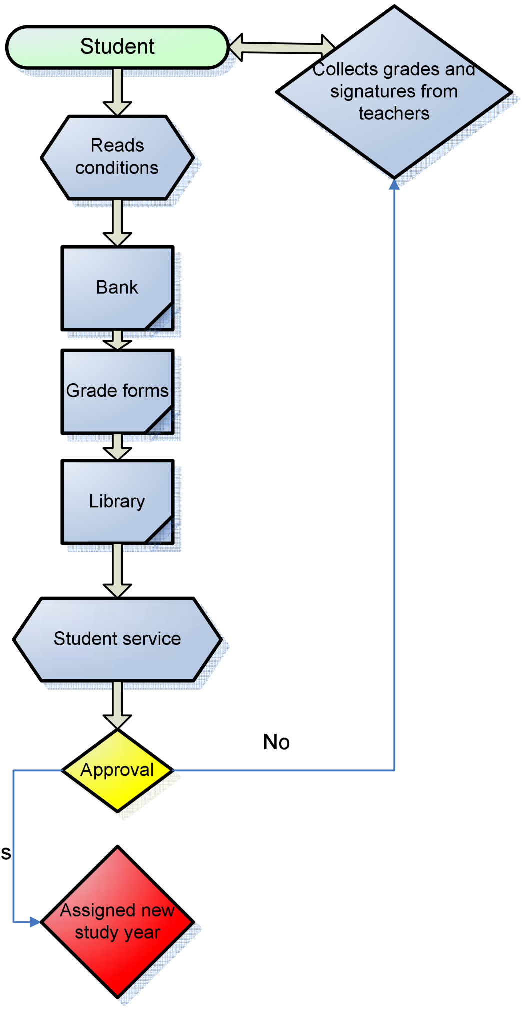

Fig. 2. Student's application process

The question is: *Where is the problem here*?

The employees at the Faculty have recognized the problems that occurred during the application process and have decided to make changes in the part that can be changed by the Faculty and that is in the student service part.

The identification of the process is the first phase from the so-called Nutshell approach for workflow modeling. This approach is organized into four phases: 1) Framing the process; 2) Understanding the current (as-is) process; 3) Design the new (to-be) process; and 4) Developing use case scenarios.[7].

In this way we are able to finish the first step of the Nutshell approach – framing the process. We can name the process as an application process, we can identify the event that triggers the process, we can see the result achieved by the process, identify the stakeholders and the results they expect, actors, mechanisms that support the process (systems, forms, equipment), the process time and frequency. When the process is framed and the main questions are answered, the second step is to understand the current (as-is) process.

2.1. The as-is process and the problems

If we want to model the process effectively to be visible from outside it is not enough just to explain that process in words. It is important that visual aid is added. This is a basic part of the second phase of the Nutshell approach for understanding the as-is process shown visually by diagrams or drawings. At the Figure 2 we can see a very simple workflow diagram. We are all used to draw diagrams and tables to simplify our conclusions or main points. In this modeling we use the so-called Swimlane diagram that show what is done, by whom, and in what sequence. Some authors describe the three Rs: roles, rules and routes [8]. Just as a fact it is useful to mention that every year (every September) there are approximately 300 students per year applying for new study year. For three years (except the students applying in the 1st year) there are 900 students applicants. Every student should get a signature or a grade from approximately at least 5 (five) teachers, which is $900 \times 3 \times 5 = 112500$ signatures and grades.

Figure 3 shows the model of the student's application process using the Swimlane diagram. We can see the roles or the actors that perform the process: the Vice-Dean for education, teachers, students and the student service. We can also see their responsibilities and the routes or the workflows and decisions that connect the tasks together and therefore define the path that an individual work item will take through the process. The Faculty has noticed the following problems of the old application process. The process is too long; the student needs days, sometimes weeks to collect all signatures and grades from his/her teachers; the student has to spend time for paying all expenses in the bank because there is no such at the Faculty building; he/she has to fill a lot of application forms given by the Ministry of Education and Science; he needs to go to the student service desk at specific time period; teachers sometimes lose the grade forms, so the student service does not have information if the student really passed an exam. The improvement has to provide solutions for the above process. If everything is all right the student service needs few days to give back the student ID to the student.

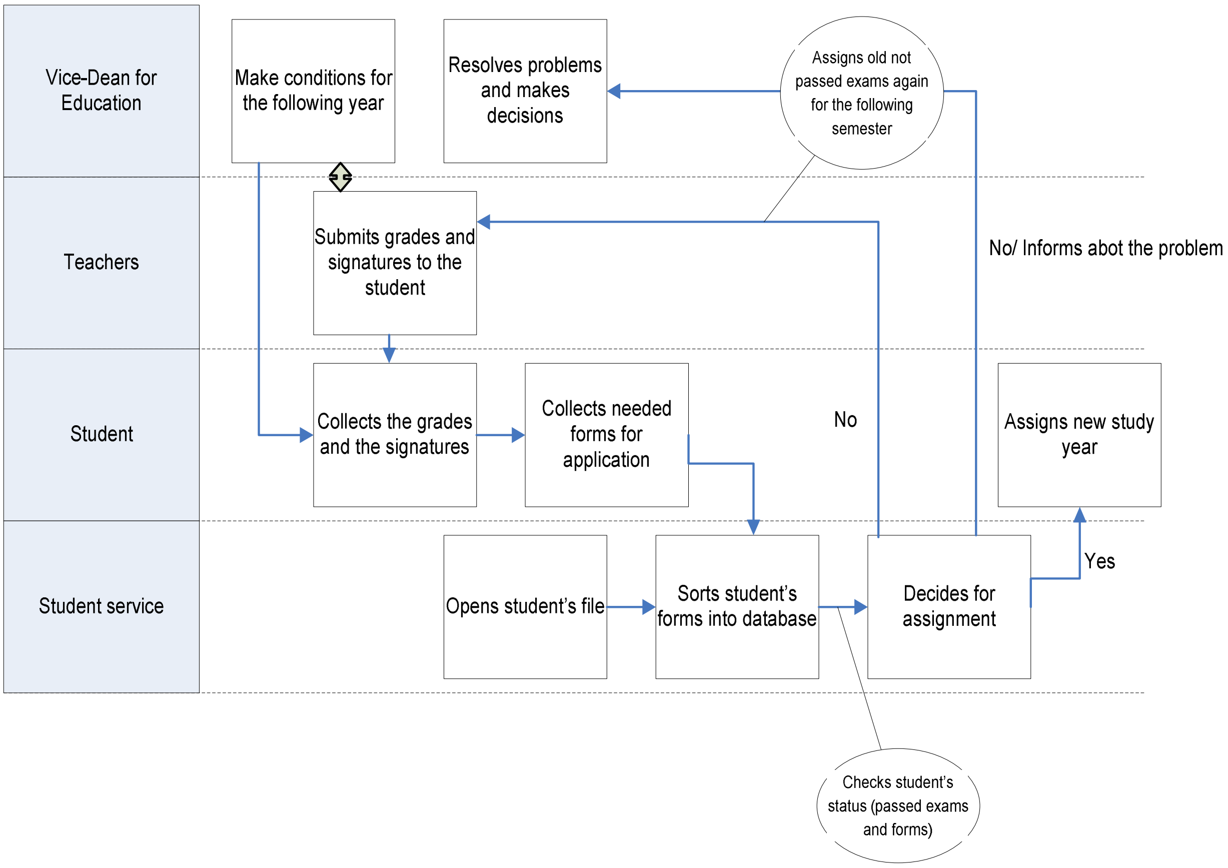

Fig. 3. Swimlane diagram of the student's application process – old process

2.2. The to-be process planning

Some of the problems the Faculty could not resolve without permission from the University management. This includes the time spent for different payments for the studies as well as for the grade forms for each exam. This regulation is for all universities in the Republic of Macedonia given by the Ministry of Education and Science in collaboration with the Ministry of Finance and there is no way to avoid it. For this reason the Faculty decided to find a solution only for the administrative part of the process where the Faculty has an influence. The changes are made on the part of registering the students in the database also in the student service for checking student's status. Now the student can check his status on his own using the database. A team has been formed and consists of the Vice-Dean for education as the leader of the team, IT professionals from the Computer Center, IT external consultants who helped the database develop and the student service administration that helped focusing on the problems that could occur during the application database development. The team decides that the most effective solution (in this pilot solution project) would be the development of the online application form. The application form can be filled out only with IT Center's approval and the student will have a permission to fill it only in the Computer Center at the Faculty. IT experts and consultants created a new IT package using several databases consisted of the following inputs:

- the student's condition (student's grades, passed exams in the previous year/semester),
- elected subjects requirements for next year,
- active subjects.

This application became active in September 2007 when students during the 15 day period, organized by their mentors, were able to fill their application form in the Computer Center at the Faculty. The Figure 4 shows the to-be Swimlane diagram of the process that has been designed.

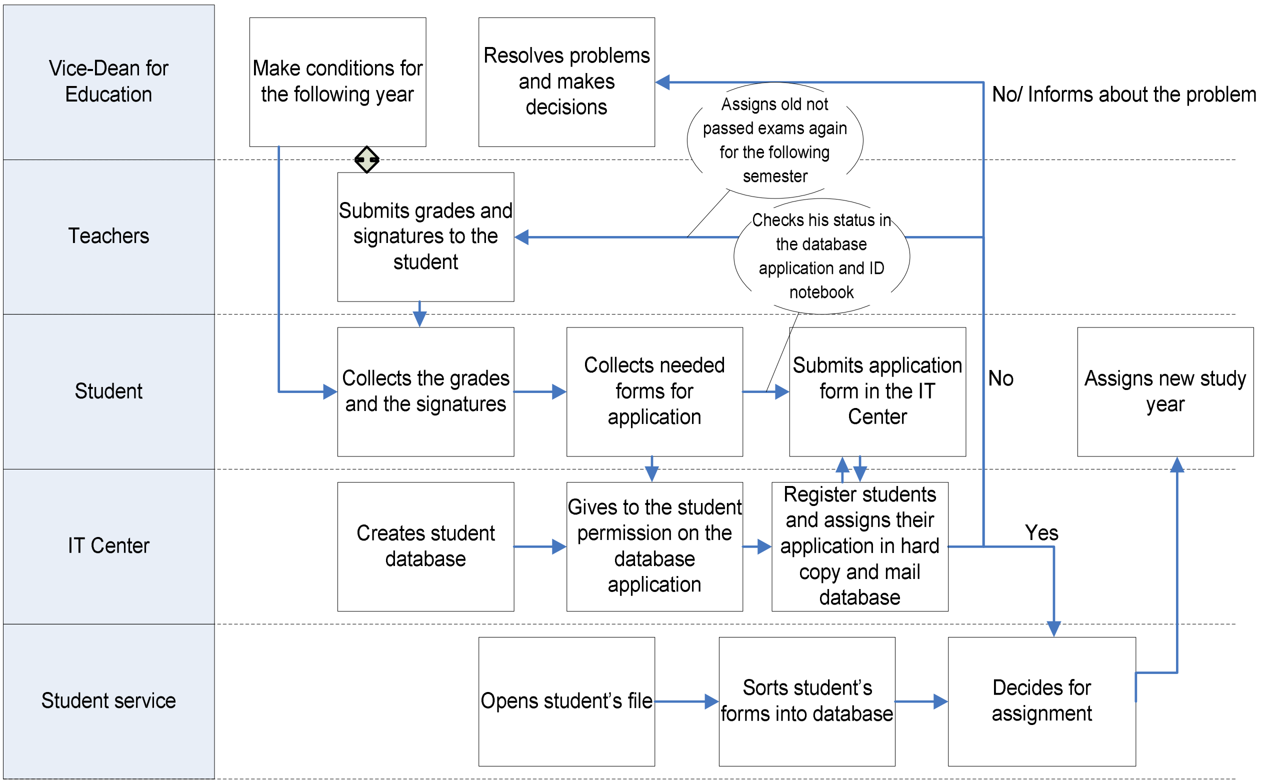

Fig. 4. Swimlane diagram of the student's application process – new process

2.3. Realization of the process

With the new database application form a new process has been made. In this process students have to go to the Computer Center bringing with them the ID notebook and grade forms for each exam in the following year. In the Computer Center they receive help for submitting the application by the IT expert. Using their own account (username and password) the students could see their status, how many exams are registered by the student service, which subjects they are allowed to attend and professors names. With this they are able to check their status and to see any of possible mistakes are made by the professors or the student service (for example, lost grade forms). When the student has checked all exams and everything is all right, he submits the form to an e-mail data base and receives a hard copy and e-mail confirmation for his application. When the student finishes the application at the Computer Center, he goes to the student service with all documents (application lists from the Ministry and statistics, the list from the obtained application, confirmation list from the bank for his expenses and ID) to receive stamp for permission to attend the next study year or the next year on condition that he finishes all exams during that year. As we can see from the Swimlane diagram (Fig. 4) with this reconstruction of the process, a new enabler is added – the IT Center.

3. RESULTS

As it was mentioned before, the purpose of the restructuring process is to make changes of an already existing process that would bring effectiveness and efficiency in the work. Some of the obstacles are bypassed with small changes in the application process but yet the total application process remains inflexible for the students. Now the student service has more secure information and reduced work with the students but another entity plus is involved in the new process (Fig. 4). On the other hand the Vice-Dean for education has relevant data for all problems as well as for all statistic data. (During the application process the Vice-Dean received information that only 10% from approximately 900 students from the three years were having problems.) The student can timely also see if there is any problem. Teachers could also have up-to date information about the interest for their classes. The student procedure now has a plus level and plus work. With this application pilot process the work of the staff is reduced which is very positive and the students can act very fast if there is any problem.

4. CONCLUSION

With the implementation of the Bologna process faculties in the Republic of Macedonia have faced a lot of problems. The real challenge for them is how to make real improvements.

The main mistake that companies and institutions make during the reconstruction process is not defining processes [7]. The real issue is to recognize where and what has gone wrong and set it right. Well-reviewed process means a process that is supported by modeling and metrics. This research article is not about finding any mistakes or recommendations, even though they would be very useful for those who are concerned, but shows to a possible way for further improvements based on the Nutshell approach and Swimlane diagram. The workflow modeling is relatively a new approach in the Business Process Reengineering (BPR) even though consultants used various simulation diagrams of the workflow to describe visually processes, but more for manufacturing equipment.

REFERENCES

[1] F. Čuš, J. Balič: *Establishing quality assurance system in Slovenian University of Maribor – University and other higher education, comparable to European system*, Maribor, Slovenia, Kopaonik, 2007.

[2] D. Runcev: *Bologna Declaration implementation experiences at the Faculty of Mechanical Engineering in Skopje – The Bologna Process and new law implementation*, Kopaonik, 2006

[3] Council of Europe: *European Higher Education Area-Joint declaration of the European Ministers of Education, Convened in Bologna on the 19th of June 1999*, 5 February 2003.

[4] V. Dukovski: *Quality Management*, „SS. Cyril and Methodious“ University, Skopje, 2003, p. 98.

[5] *WWWebster Dictionary*, copyright ©1999 (based on Merriam-Webster's Collegiate Dictionary, 10th Edition) at web site http://www.m-w.com by Merriam-Webster, Inc.

[6] WordNet 1.6, copyright ©1997 by Princeton University.

[7] A. Sharp, P. McDermott: *Workflow Modeling – Tools for Improvement and Application Development,* Artech House, Boston, London 2001, www.artechhouse.com

[8] T. Koulopoulos: *The Workflow Imperative: Building Real World Business Solutions*, New York, Van Nostrand Reinhold, 1995, p. 38.

Резиме

МОДЕЛИРАЊЕ НА ПРОЦЕСОТ ЗА СТУДЕНТСКО АПЛИЦИРАЊЕ СО ПРИМЕНА НА ПРИОДОТ „NUTSHELL“

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Клучни зборови: моделирање; процес; приод "Nutshell"; Swimlane-дијаграм; промени

Оваа статија опишува симулација на моделирање на веќе постоен процес на студентска апликација за нова учебна година (зимски семестар) на Машинскиот факултет во Скопје. Статијата се базира на примена на таканаречениот приод „корупка од орев“ (Nutshell approach), кој овозможува дефинирање на веќе постојните процеси, нивно претставување со визуелни техники (графикони, дијаграми) и креирање на сценарија за подобрување на процесите (доколку тоа е потребно). Во оваа статија симулацијата е направена врз основа на веќе имплементирани промени во процесите, односно симулирана е техниката на користење на приодот „Nutshell“ на веќе усвоените промени со цел да се воочат карактеристиките на процесот каков бил (каков што е) и каков ќе биде (во нашиот случај веќе имплементиран: да биде), како и да се дефинираат актерите во процесот. При употребата на приодот „Nutshell“ користени се техники за визуелно претставување на процесите кои се неопходна алатка во процесот на моделирање. Во оваа статија е употребуван таканаречениот базен (Swimlane) дијаграм.

За податоците изнесени во оваа статија се користени материјали од Машинскиот факултет во Скопје и се консултирани лица директно инволвирани во процесот на формирање на промените на апликацијата.

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IMPACT OF PERIODIC CHANGING DEMAND TO SUPPLY CHAIN INVENTORIES

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Abstract: Many companies achieve significant competitive advantage by the way they configure and manage their supply chain operation. In Supply Chain Management, the overall supply chain evaluation needs to include the bullwhip effect. It represents the amplification of the order variability in a supply chain. It is understood that the demand forecast variance contributes to that effect in the chain. With this understanding, the authors experimented with a case of changing demand in periodic 10 % increases and later in the same decreases. Four inventory control policies (P) for both stages in the chain have been studied: to keep in stock, i) one period's demand at both stages – P_{11}, ii) two periods' demand at both stages – P_{22}, iii) one period's demand at the first stage and two periods' demand at the second stage – P_{12}, and iv) the opposite as before – P_{21}. Increasing variability of production orders and inventory levels up the supply chain is evident. The effect indicates a lack of synchronization among supply chain members because of corrupt key information about actual demand. Possible actions concerned with coordinating the activities of the operations in the chain are described.

Key words: supply chain; inventory control policy; demand fluctuation; bullwhip effect

1. INTRODUCTION

Many companies have enjoyed a significant success due to the unique ways in which they have organized their supply chains. The objective of supply chain management is to provide a high velocity flow of high quality, relevant information that will enable suppliers to provide an uninterrupted and precisely timed flow of materials to customers. The idea is to apply a total systems approach to managing the entire flow of information, materials, and services from raw materials suppliers through factories and warehouses to the end customer [1].

A supply chain, logistics network, or supply network is a coordinated system of organizations, people, activities, information and resources involved in moving a product or service in physical or virtual manner from a supplier to a customer. How to develop a production – distribution network to satisfy response time constraints and minimize the total cost of production and distribution is a challenge when supply chains are developed [2].

Today, the ever increasing technical complexity of standard consumer goods, combined with the ever increasing size and depth of the global market has meant that the link between the consumer and the vendor is usually only the final link in a long and complex chain or network of exchanges [3].

Although many companies and corporations today are of importance not just on national but also on a global scale, none are of a size that enables them to control the entire supply chain, since no existing company controls every link from raw material extraction to the consumer [4].

The organization of the paper is as it follows. In the next section we provide some basic facts of the bullwhip effect and a brief literature review of the research work. In section 3 the details of the investigated case of simple supply chain model are presented. Section 4 describes actions against the bullwhip effect. Concluding remarks are given in the final section.

2. LITERATURE REVIEW FOR THE BULLWHIP EFFECT

The term *bullwhip effect* was coined by the Procter & Gamble management who noticed an amplification of information distortion as order information travelled up the supply chain. The bullwhip effect (or *whiplash effect*) is an observed phenomenon in forecast-driven distribution channels. The effect indicates a lack of synchronization among supply chain members. Even a slight change in customer sales ripples backward in the form of amplified oscillations upstream, resembling the result of a flick of a bullwhip handle. Because the supply patterns do not match the demand patterns, inventory accumulates at various stages (Fig. 1).

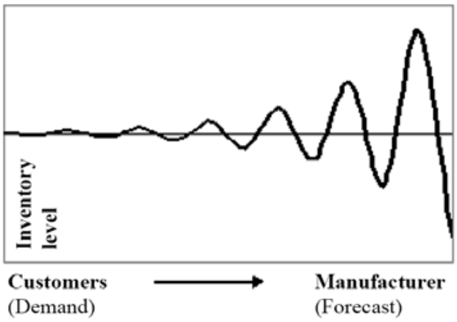

Fig. 1. Inventory variability amplification in a supply chain due to the bullwhip effect

The concept has its roots in Forrester's *Industrial Dynamics* [5]. Because the customer demand is rarely perfectly stable, businesses must forecast demand in order to properly position inventory and other resources. Variability coupled with time delays in the transmission of information up the supply chain and time delays in manufacturing and shipping goods down the supply chain create the bullwhip effect. Forecasts are based on statistics, and they are rarely perfectly accurate. Because forecast errors are given, companies often carry an inventory buffer called "safety stock". Moving up the supply chain from the end-consumer to the raw materials supplier, each supply chain participant has greater observed variation in demand and thus a greater need for safety stock. In periods of a rising demand, down-stream participants will increase their orders. In periods of a falling demand, orders will fall or stop in order to reduce inventory. The effect is that variations are amplified as one moves upstream in the supply chain (further from the customer). The bullwhip effect is also attributed to the separate ownership of different stages of the supply chain. Each stage in such a structured supply chain tries to amplify the profit of the respective stages, thereby decreasing the overall profitability of the supply chain [1, 6–8]. An important question is: Do companies in a supply chain agree to share demand information? Some solutions to both situations are presented in [9].

A very simplified mechanism of the bullwhip effect is described here. If a retail store that typically sells 50 units a week all of a sudden sells nearly 100 per week, then this is going to result in the supplier producing more than 100 in order to have a safety stock for its customer. Now the supplier is producing $100 + X$.

The supplier's supplier now needs to ramp up in order to have a safety stock that results in $100 + X + Y$. As we go down the supply chain, more variables are tagged onto the end of that equation.

The problem is, the supply chain as a whole needs to be able to satisfy the same demand. If the retail store needs 100 units, then everyone in the chain should be prepared to supply 100 units.

Factors contributing to the bullwhip effect:

- forecast errors,
- overreaction to backlogs,
- lead time (of information – production orders and of material) variability,
- no communication and no coordination up and down the supply chain,
- delay times for information and material flow,
- batch ordering (larger orders result in more variance),
- rationing and shortage gaming,
- price fluctuations, product promotions, free return policies, inflated orders.

Anderson *et al.* [10] present a system dynamics model to investigate upstream volatility in the machine tools industry. By a series of simulation experiments they test several hypotheses about the nature of the bullwhip effect, e.g. how production lead times affect the entire supply chain.

To address the bullwhip effect, many techniques are employed to manage various supply chain processes, such as order information sharing, demand forecasting, inventory management, and shipment scheduling [11, 12].

Lee *et al.* [6] cite several factors causing the bullwhip effect under rational decision making on the part of chain members, and suggest methods (such as information sharing and strategic partnerships) to decrease the amount of variance amplification in the supply chain.

This phenomenon is not harmful by itself, but because of its consequences [13]:

- Excessive inventory investments: Since the bullwhip effect makes the demand more unpredictable, all companies need to safeguard themselves against the variations to avoid stock-outs.

- Poor customer service levels: Despite the excessive inventory levels mentioned in the first consequence, demand unpredictability may cause stock-outs anyway.
- Lost revenues: In addition to the poor customer service levels of the second consequence, stock-outs may also cause lost revenues.
- Reduced productivity: Since revenues are lost, operations are less cost efficient.
- More difficult decision-making: Decision-makers react to demand fluctuations and adapt (production and inventory) capacities to meet peak demands.
- Sub-optimal transportation: Transportation planning is made more difficult by demand uncertainties induced by the bullwhip effect.
- Sub-optimal production: As transportation, greater demand unpredictability causes missed production schedules.

3. CASE WITH A SIMPLE SUPPLY CHAIN MODEL

The objective of this paper is to illustrate and discuss the impact of inventory control policies at different demand processes (the bullwhip effect). The results (changes in order sizes and stocks) for all stages in a supply chain are compared.

We consider a periodic review system in discrete time, since retailers tend to order on a frequent time basis, for instance daily, weekly or monthly, a variable amount of products.

The main cause of variability through the chain is a perfectly understandable and rational desire by the different links in the supply chain to manage their production rates and stock levels sensibly [14].

3.1. Circumstances: Changing demand in periodic 10 % increases and later in 10 % decreases

Tables 1 to 4 present a two-stage supply chain (very simple model, but widely used in real situations, see Fig. 2) for an item with sales growing at 10 % per period for 4 periods and then shrinking by 10 % for 4 more periods. There is no capacity limit for the inventory level for each stage in our model.

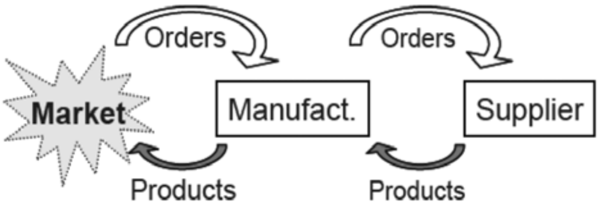

Fig. 2. Presentation of a two-stage supply chain

P_{11}: Both stages in the chain work on the principle that they will keep in stock one period's demand – Eq. (1). Orders and deliveries are made in the same period. In this simple case, the decision of how much to produce each period was governed by the following relationship:

$$\text{Production rate} = 2 \times \text{demand} - \text{starting stock}\ (\geq 0) \qquad (1)$$

The market demand has been running at a rate of 100 items per period, but in period 2 demand increases to 110 items per period (+10 %). And so on.

Table 1

Changes of production rates and stock levels (continual 10 % demand changes, P_{11}).

Period	Demand (market)	Manufacturer		Supplier	
		Production rate	Stock start/finish	Production rate	Stock start/finish
1	100	100	100 / 100	100	100 / 100
2	110	120	100 / 110	140	100 / 120
3	121	132	110 / 121	144	120 / 132
4	133	145	121 / 133	158	132 / 145
5	146	159	133 / 146	173	145 / 159
6	131	116	146 / 131	73	159 / 116
7	118	105	131 / 118	94	116 / 105
8	106	94	118 / 106	83	105 / 94
9	95	84	106 / 95	74	94 / 84

The column headed 'Stock' for each level of supply shows the starting stock at the beginning of the period and the finish stock at the end of the period. At the beginning of the period 2, the manufacturer has 100 units in stock (that being the rate of demand up to the period 2). Demand in the period 2 is 110 and so the manufacturer knows that it would need to produce sufficient items to finish up at the end of the period with 110 in stock (this being the new demand rate). To do this, it needs to manufacture 120 items; these will supply demand and leave a finished stock of 110 items. The beginning of period 3 finds the manufacturer with 110 items in stock. Demand is 121 items and therefore its production rate to maintain a stock level of 121 will be 132 items per period. And so on for all observed periods. The manufacturer never operates at a steady rate in such changing conditions. We should note that the first change in the demand of only 10 % has produced a fluctuation of 20 % in the manufacturer's production rate.

The same logic is used through to the supplier. At the beginning of the period 2, the supplier has 100 items in stock. The demand which it has to supply in the period 2 is derived from the production rate of the manufacturer. This has risen to 120 in the period 2. The supplier therefore has to produce sufficient to supply the demand of 120 items and leave one period's demand (now 120 items) as its finish stock. A production rate of 140 items per period will achieve this. It will therefore start the period 3 with an opening stock of 120 items, but the demand from the manufacturer has now risen to 132 items. It therefore has to produce sufficient to fulfil this demand of 132 items and leave 132 items in stock. To do this, it must produce 144 items in the period 3. And so on. The fluctuation has been even greater than that in the manufacturer's production rate.

Table 1 clearly shows the bullwhip effect. The sales go up 46 % (100 to 146), and thereafter go down 35 % (146 to 95). Orders to the manufacturer go up by 59 % (100 to 159), and then down by 47 % (159 to 84). Orders to the supplier go up by 73 % (100 to 173) and then down immediately by 58 % (173 to 73).

P_{22}: Both stages in the chain work on the principle that they will keep in stock two periods' demand – Eq. (2). Orders and deliveries are made in the same period. The situation is shown in Table 2. In this case, the decision of how much to produce each period was governed by the following relationship:

$$\text{Production rate} = 3 \times \text{demand} - \text{starting stock } (\geq 0) \qquad (2)$$

The fluctuation of the production rate has been extreme. In the period 2 the sales of 110 units result in the ending manufacturer's stock of 90, which is thereafter corrected by an order and delivery of 130 units to bring the period 3 beginning stock to its desired level of 220. For all other periods see Table 2.

Table 2

Changes of production rates and stock levels (continual 10 % demand changes, P_{22}).

Period	Demand (market)	Manufacturer		Supplier	
		Production rate	Stock start / finish	Production rate	Stock start / finish
1	100	100	200 / 200	100	200 / 200
2	110	130	200 / 220	190	200 / 260
3	121	143	220 / 242	169	260 / 286
4	133	157	242 / 266	185	286 / 314
5	146	172	266 / 292	202	314 / 344
6	131	101	292 / 262	0	344 / 243
7	118	92	262 / 236	33	243 / 184
8	106	82	236 / 212	62	184 / 164
9	95	73	212 / 190	55	164 / 146

The sales go up 46 %, and thereafter go down 35 % in total. Orders to the manufacturer go up by 72 % (100 to 172), and then down by 58 % (172 to 73). Even more dramatically, orders to the supplier go up by 102 % – more than doubled (100 to 202) and then down by 100 % (202 to 0). In the 6th period the production at the supplier is completely shut down. The span-width of the supplier's production rate is from 0 to 202.

It can be seen that the manufacturer orders to the supplier experience demand fluctuate far more drastically than the market demand. Small movements at the end of the supply chain trigger exponential movements down the chain in order to prevent stock-outs.

The changing situation in both scenarios P_{11} and P_{22} regarding variability of stocks and production orders during 9 periods is shown in Figs. 3 and 4.

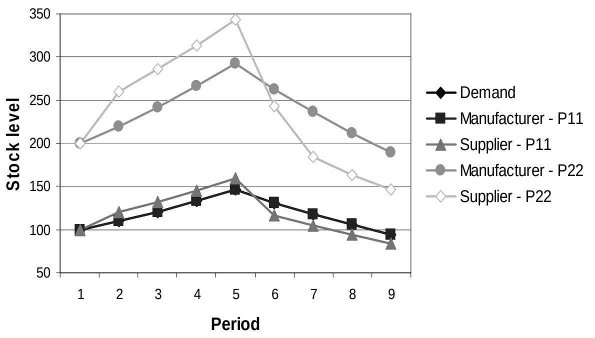

Fig. 3. Stock variability in a two-stage supply chain (policies: P_{11}, P_{22})

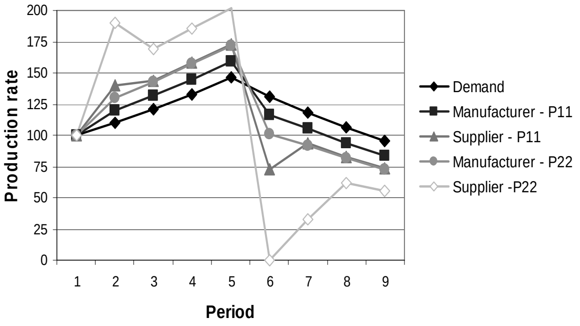

Fig. 4. Production rate variability in a two-stage supply chain (policies: P_{11}, P_{22})

P_{12}: The stages in the chain work on the principle that they will keep in stock one period's demand at the first stage (1) and two periods' demand at the second stage (2). Orders and deliveries are made in the same period.

Table 3

Changes of production rates and stock levels (continual 10 % demand changes, P_{12}).

Period	Demand (market)	Manufacturer		Supplier	
		Production rate	Stock start / finish	Production rate	Stock start / finish
1	100	100	100 / 100	100	200 / 200
2	110	120	100 / 110	160	200 / 240
3	121	132	110 / 121	156	240 / 264
4	133	145	121 / 133	171	264 / 290
5	146	159	133 / 146	187	290 / 318
6	131	116	146 / 131	30	318 / 232
7	118	105	131 / 118	83	232 / 210
8	106	94	118 / 106	72	210 / 188
9	95	84	106 / 95	64	188 / 168

The situation in changing market demand is at the manufacturer's site the same as in the case of P_{11}. Orders to the supplier go up by 87 % (100 to 187) and then down immediately by 84 % (187 to 30, the span-width is equal).

P_{21}: The stages in the chain work on the principle that they will keep in stock two periods' demand at the first stage and one period's demand at the second stage. Orders and deliveries are made in the same period.

Table 4

Changes of production rates and stock levels (continual 10 % demand changes, P_{21}).

Period	Demand (market)	Manufacturer		Supplier	
		Production rate	Stock start / finish	Production rate	Stock start / finish
1	100	100	200 / 200	100	100 / 100
2	110	130	200 / 220	160	100 / 130
3	121	143	220 / 242	156	130 / 143
4	133	157	242 / 266	171	143 / 157
5	146	172	266 / 292	187	157 / 172
6	131	101	292 / 262	30	172 / 101
7	118	92	262 / 236	83	101 / 92
8	106	82	236 / 212	72	92 / 82
9	95	73	212 / 190	64	82 / 73

For example, in the period 5 the sales of 146 units result in manufacturer's ending stock of 120, which is thereafter corrected by an order and delivery of 172 units to bring the period 6 beginning stock to its desired level of 292. The manufacturer's production rates are between 73 and 172, and between 30 and 187 at the supplier. Both scenarios regarding variability of stocks and production orders are shown in Figs. 5 and 6.

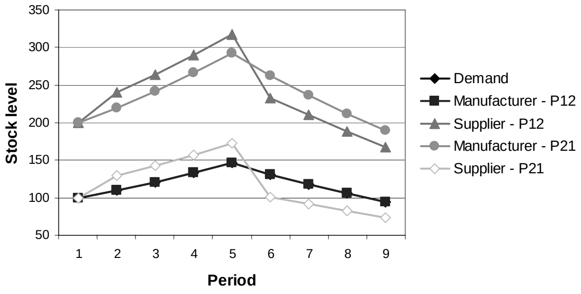

Fig. 5. Stock variability in a two-stage supply chain (policies: P_{12}, P_{21})

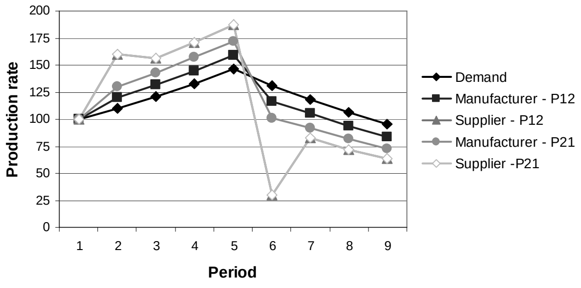

Fig. 6. Production rate variability in a two-stage supply chain (policies: P_{12}, P_{21}).

The comparison of the last two policies shows that there is no difference in production rates at the supplier's site. Logically, appropriate differences are in stock levels. Stock levels at the supplier's site are in case of P_{21} lower than at P_{22} and P_{12}, and, in spite of doubled stocks at the manufacturer, even slightly lower (average value: 116,7 versus 117,2) than at P_{11}!

Relations between orders and stocks for all applied policies are summarized in Table 5.

Table 5

Max/Min ratios for 9 observed periods.

Measure	Max/Min ratio							
	P_{11}		P_{22}		P_{12}		P_{21}	
	M	S	M	S	M	S	M	S
Production rate	1,89	2,37	2,36	∞	1,89	6,23	2,36	6,23
Stock level	1,54	1,89	1,54	2,36	1,54	1,89	1,54	1,89

Comment: M – Manufacturer, S – Supplier, Market's Max/Min Ratio: 1,54

The presented case and its situation are very real. We have seen examples where suppliers have been shut down completely for many periods when the orders at the end of the supply chain are reduced only slightly! Retailers often make unexpected promotions to increase the demand at some periods. As a result, although the demand for some specific periods might increase, some customers will delay or reduce their next purchases. This will decrease the customers' demands in the subsequent periods and uncertainty in the supply chain will increase [15].

It is important to note that besides stock effects, similar problems would be extant in manufacturing capacity requirements, response times, and obsolescence. The shown case does not include any time lag between a demand occurring in one part of the supply chain and it being transmitted to its supplier. In practice there will be such a lag!

4. PREVENTIVE MEASURES TO THE BULLWHIP EFFECT

The key question becomes: How can the bullwhip effect be ameliorated? Companies must understand fully its main causes and implement some new strategies [16]. Different actions are possible:

- Minimize the cycle time in receiving projected and actual demand information.
- Establish the monitoring of actual demand for product to as near a real time basis as possible.
- Understand product demand patterns at each stage of the supply chain.
- Increase the frequency and quality of collaboration through shared demand information.
- Minimize or eliminate information queues that create information flow delays, centralize demand information.
- Eliminate inventory replenishment methods that launch demand lumps into the supply chain.
- Reduce the order sizes and implement capacity reservations.
- Eliminate incentives for customers that directly cause demand accumulation and order staging prior to a replenishment request, such as volume transportation discounts.
- Offer your products at consistently good prices to minimize buying surges brought on by temporary promotional discounts.
- Minimize incentive promotions that will cause customers to delay orders and thereby interrupt smoother ordering patterns; identify, and preferably, eliminate the cause of customer order reductions or cancellations.
- Decision-makers should react to demand fluctuations and adapt capacities to meet peak demands.
- Implement special purchase contracts in order to specify ordering at regular intervals, limit free return policies.

5. CONCLUSION

Superior supply chains are one of the best ways to compete in today's marketplaces. For make-to-stock production systems, which are involved in different supply chains, the production plans and activities are based on demand forecasting. The orders are supplied by stock inventory, in which the policy emphasizes the immediate delivery of the order, good quality, reasonable price, and standard products. The customers expect that delays in the order are inexcusable, so the supplier must maintain sufficient stock [17].

It has been recognized that demand forecasting and ordering policies are two of the key causes of the bullwhip effect. Basically, the bullwhip effect is safety stock for safety stock; because suppliers hold extra stock for their customers the same way retailers hold extra stock for their customers.

Suppliers need safety stock, for the safety stock [14].

Situations where information is not shared between the manufacturer (with chained suppliers) and the retailers may cause a heavier burden on the safety stock or a greater expenditure in shortage cost. The negative effect on business performance is often found in excess stocks, quality problems, higher raw material costs, overtime expenses and shipping costs. In the worst-case scenario, the customer service goes down, lead times lengthen, sales are lost, costs go up and capacity is adjusted. An important element to operating a smooth flowing supply chain is to mitigate and preferably eliminate the bullwhip effect.

In the paper we experimented with a special case of a simple two-stage supply chain using four inventory control policies. Results are discussed and shown in tables and charts. They illustrate how the parameters of the inventory control policy induce or reduce the bullwhip effect. The inventory level of the upstream stage is not always larger than that of the downstream stage of the chain. This is evident at policies P_{11} and P_{22}, when the market demand is decreasing.

There were no capacity limits for the inventory level for the stages of the supply chain in our model. For future study, we will focus on incorporating such restrictions at all stages of a supply chain. We will include more chain stages. The investigation will be based on spreadsheet simulation.

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REFERENCES

[1] R. B. Chase, N. J. Aquilano, F. R. Jacobs: *Operations management for competitive advantage*, McGraw-Hill/Irwin, Boston, 2001, pp. 330–347.

[2] D. R. Sule: *Production planning and industrial scheduling*, CRC Press, Boca Raton, 2008, pp. 5–6.

[3] S. M. Gilbert, R. H. Ballou: Supply chain benefits from advanced customer commitments, *Journal of Operations Management*, **18**, 1, 61–73 (1999).

[4] M. Rudberg, J. Olhager: Manufacturing networks and supply chains: An operations strategy perspective, *Omega*, **31**, 1, 29–39 (2003).

[5] J. W. Forrester: *Industrial dynamics*, MIT Press, Cambridge, 1961.

[6] L. H. Lee, V. Padmanabhan, S. Whang: Information distortion in a supply chain: the Bullwhip Effect, *Management Science*, **43**, 4, 546–558 (1997).

[7] R. Metters: Quantifying the Bullwhip Effect in supply chains, *Journal of Operations Management*, **15**, 2, 89–100 (1997).

[8] D. Simchi-Levi, P. Kaminsky, E. Simchi-Levi: *Designing and managing the supply chain*, McGraw-Hill, New York, 2003.

[9] T. Moyaux, B. Chaib-Draa, S. D'Amours: Design, Implementation and Test of Collaborative Strategies in the Supply Chain, *Studies in Computational Intelligence*, **28,** 247–272 (2006).

[10] E. G. Anderson, C. H. Fine, G. G. Parker: Upstream Volatility in the Supply Chain: The Machine Tool Industry as a Case Study, *Production and Operations Management*, **9**, 3, 239–261 (2000).

[11] J. Dejonckheere, S. M. Disney, M. R. Lambrecht, D. R. Towill: Measuring and avoiding the bullwhip effect: a control theoretic approach, *European Journal of Operational Research*, **47**, 3, 567–590 (2003).

[12] J. Li, M. J. Shaw, R. T. Sikora: The effects of information sharing strategies on supply chain performance, Technical Report, 2001.

[13] C. Carlsson, R. Fullér: Soft computing and the bullwhip effect, *Economics and Complexity*, **2**, 3, 1–26 (2000).

[14] N. Slack, S. Chambers, R. Johnston: *Operations Management*, Prentice Hall, Harlow, 2001, pp. 433–443.

[15] C. Lin, Y.-T. Lin: Mitigating the bullwhip effect by reducing demand variance in the supply chain, *International Journal of Advanced Manufacturing Technology*, **28**, 328–336 (2006).

[16] R. M. Donovan: Supply Chain Management – Cracking the Bullwhip Effect, 2002, *Available from:* http://www.edm1.com/donovan.pdf, *Accessed:* 2007-06-10.

[17] D. W. Fogarty, J. H. Blackstone, T. R. Hoffmann: *Production & inventory management*, South-Western, Cincinnati, 1991.

Резиме

ВЛИЈАНИЕТО НА ПЕРИОДИЧНО ПРОМЕНЛИВИТЕ ПОТРЕБИ ВРЗ ЗАЛИХИТЕ ВО СНАБДУВАЧКИТЕ СИНЏИРИ

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Клучни зборови: снабдувачки синџир; принципи на управување со залихи; флуктуирање на побарувањата; „камшик“ ефект

Голем број компании постигнуваат значителна конкурентска предност преку приспособување и управување на операциите во снабдувачкиот синџир. Во управувањето на снабдувачките синџири вкупната процена на снабдувачкиот синџир треба да го вклучи и „камшик“-ефектот. Тоа го претставува проширувањето на варијациите на нарачките во снабдувачкиот синџир. Јасно е дека варирањето на прогнозата за потребите придонесува за овој ефект. Во оваа смисла, авторите истражуваа случај со променлива потреба од периодично зголемување и намалување од 10%. Проучени се четири принципи на управување со залихи (P) за две нивоа во синџирот: задржување во склад, 1) потреба од еден период за двете нивоа – P_{11}, 2) потреба од два периода за двете нивоа – P_{22}, 3) потреба од еден период за првото ниво и два периода за второто ниво – P_{12}, и 4) спротивно на претходното – P_{21}. Зголемувањето на варирањето на нарачките и зголемувањето на залихите значително го зголемуваат снабдувачкиот синџир. Ефектот покажува недостиг од синхронизација помеѓу члeновите на снабдувачкиот синџир, поради неточни клучни информации за тековните потреби. Покрај ова, претставени се можните акции кои ја земаат предвид коoридинацијата на активностите од операциите во синџирот.

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Original scientific paper

FAST ESTIMATAION OF PRODUCTION TIMES AS THE DECISION SUPPORT FOR DELIVERY TIMES AND PRODUCTION COSTS

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Abstract: Very frequently we must answer some important requests for offers, generated for individual or batch production, for example: a great number of requested offers for production of products at once, small batches with very rare repetition, frequent changes of priorities during production, short deadlines of delivery, market demands for approaching prices of the individual or batch production near the prices of mass production, etc. The purpose of this research was establishing possible connections between sketch features and necessary production times for manufacturing products. Research of the connection between production time and features of products gives us as a result the technological knowledge base and the regression equations.

Key words: fast process planning; technological knowledge base; stepwise multiple linear regression

1. INTRODUCTION

The process planning could be presented like a balance between producing a part meeting functional requirements, minimal production time and minimal production cost. The relation between part manufacturing, production time and cost certainly exists but it is not always very clear.

The operations defined in the process planning have to be put in certain order according to the precedence relationships based on technical or economical constraints. The sequence of operations depends on many influences such as:

a) nature of the material,
b) general shape of the part,
c) required level of accuracy,
d) blank size,
e) number of parts in the batch,
f) possible choice of machine tools, etc.

The expected difficulties in the process of solving the operations sequence can be: pattern recognition, selection of datum, connection between machining surfaces and type of operations, machining tools, tools, positioning and holding of workpiece, etc.

2. SEQUENCING OF OPERATIONS AND ESTIMATION OF PRODUCTION TIMES

Few approaches in sequence operations and production time's estimation can be mentioned.

The first approach named *Matrix method* [1, 2] can be described as operations defined by putting them in certain order according to the precedence relationship based on technical or economical constraints.

The shape complexity approach as the second possible approach for production time's estimation is defined through entropy as a measure of sample randomness [3]. The entropy is expressed as $H = -\Sigma p_i \log_2 p_i$, where p_i is the probability of a certain outcome (angle change along contour in this case). The ultimate goal is to calculate the shape entropy as a measure of shape complexity. The shape shown in Fig. 1 has the entropy of $H = 2.052$. Of course, there is a very complex question. How to connect in a unique manner shape complexity with the technological procedure and production times / costs?

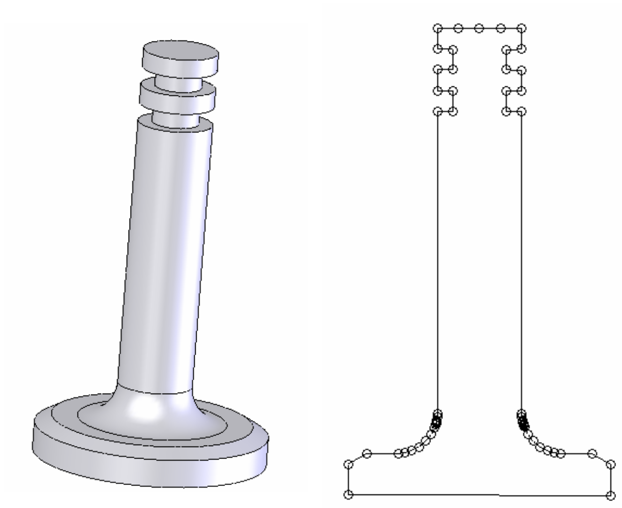


Fig. 1. Contour of a valvet approximated by splines & lines

The third approach named *Variants of process planning* [4, 5] can be explained as production time's estimation. For example, estimation of production times & costs by web application for different variants of product production were developed (Fig. 2a, 2b). The selected variant of product production is the result of the product shape (Fig. 3), way of tightening (Fig. 2a, 2b), roughness surface and kind of machine tools. Thus, production times and costs are a result of the observed process planning variant.

The fourth approach named *Operation sequencing* [1, 6] can be explained as development of original web application by Microsoft .net technology and Flash (temporary site http://www.igorm.net/studadmin/). The goal was to define the simple procedure for definiting the operations sequencing for every surface of the part. The main criteria were satisfaction of the requested geometrical and dimensional tolerance, roughness, etc.

The fundamental idea for sequencing operations (Fig. 4, 5, 6) is the shape recognition, determination between dimensional & geometrical tolerance with the requested process roughness, calculation tolerance and cutting addition and final sequence operation (Fig. 4). Web site for this application would be at http://ptp.fsb.hr.

The fifth approach named *Basic technological operations* [7, 8, 9, 10, 11] can be explained as development of the original knowledge base of the fundamental, the most frequent operations.

What can we put as the characteristics for the previous first four approaches for the possible estimation production times? First, problems with the insufficient generalization level of the used procedure, too complicated calculation, insufficient level of automation of solutions generating in IT application, etc. In this paper the fifth approach would be discussed in more details.

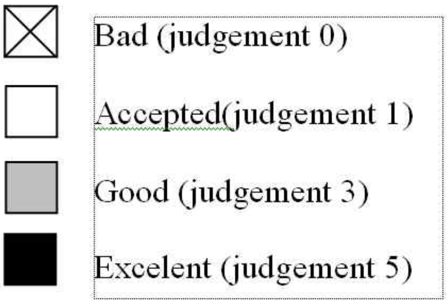


Fig. 2a. Selection of machine tools – case for conical machining

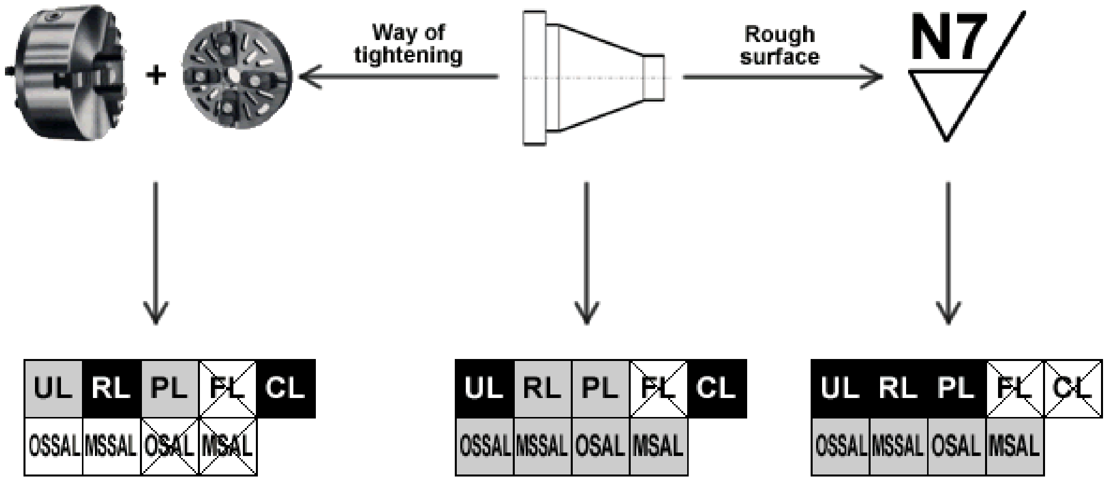
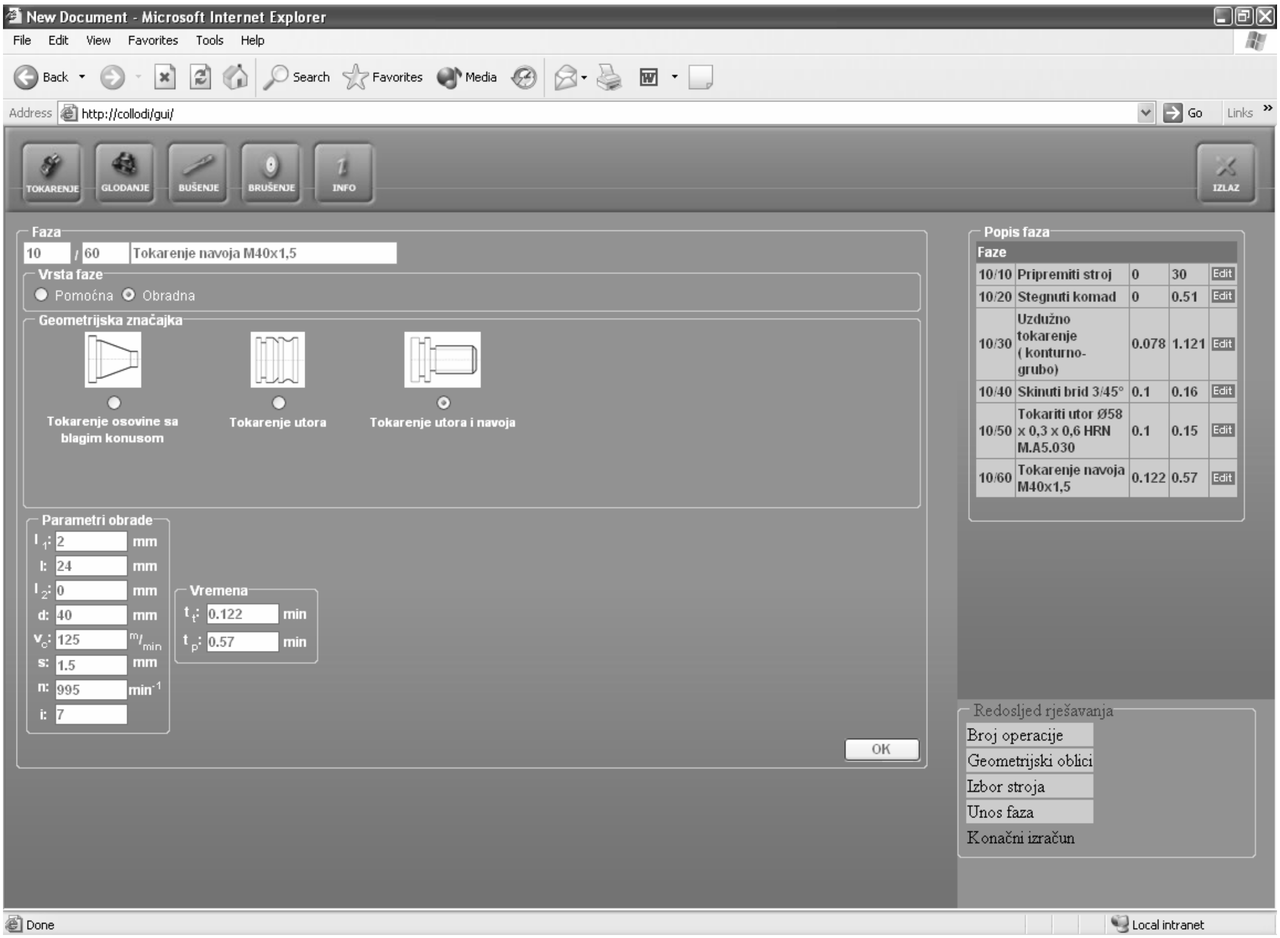


Fig. 2b. Selection of machine tools – case for conical machining



Faza: 10 / 60 Tokarenje navoja M40x1,5

Vrsta faze: ○ Pomoćna ● Obradna

Geometrijska značajka:
○ Tokarenje osovine sa blagim konusom
○ Tokarenje utora
● Tokarenje utora i navoja

Parametri obrade:
l_1: 2 mm
l: 24 mm
l_2: 0 mm
d: 40 mm
v_c: 125 $^m/_{min}$
s: 1.5 mm
n: 995 min^{-1}
i: 7

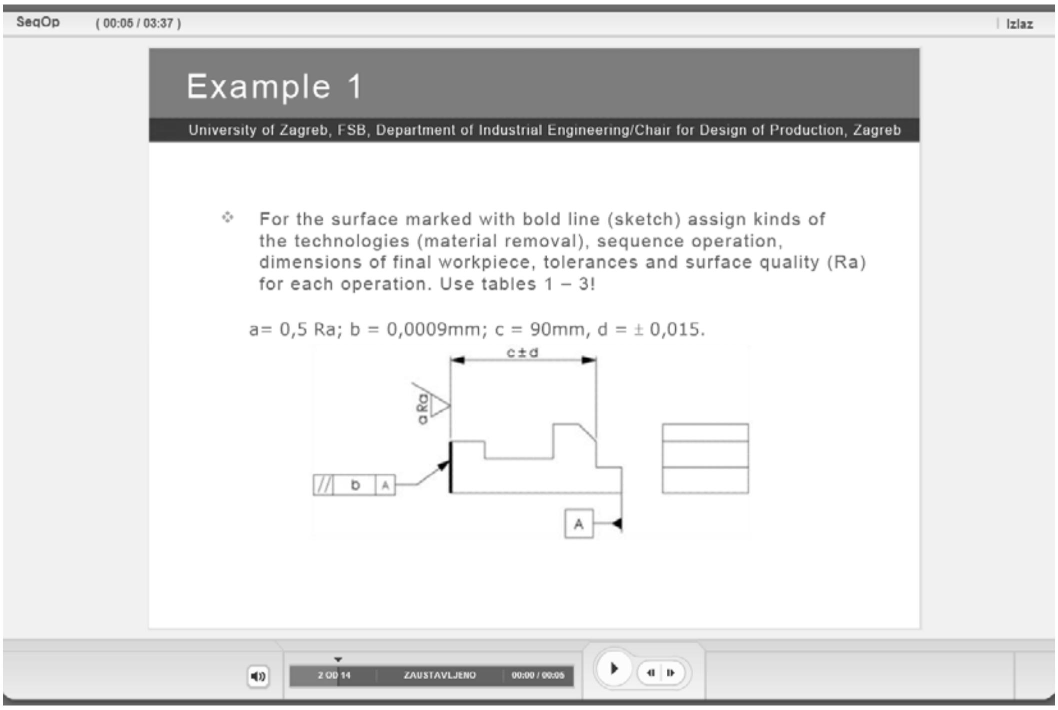
Vremena:
t_t: 0.122 min
t_p: 0.57 min

Popis faza

Faze				
10/10	Pripremiti stroj	0	30	Edit
10/20	Stegnuti komad	0	0.51	Edit
10/30	Uzdužno tokarenje (konturno-grubo)	0.078	1.121	Edit
10/40	Skinuti brid 3/45°	0.1	0.16	Edit
10/50	Tokariti utor Ø58 x 0,3 x 0,6 HRN M.A5.030	0.1	0.15	Edit
10/60	Tokarenje navoja M40x1,5	0.122	0.57	Edit

Redosljed rješavanja
- Broj operacije
- Geometrijski oblici
- Izbor stroja
- Unos faza
- Konačni izračun

Fig. 3. Phase – turning of threads with selection shape part, cutting parameters and times



Example 1

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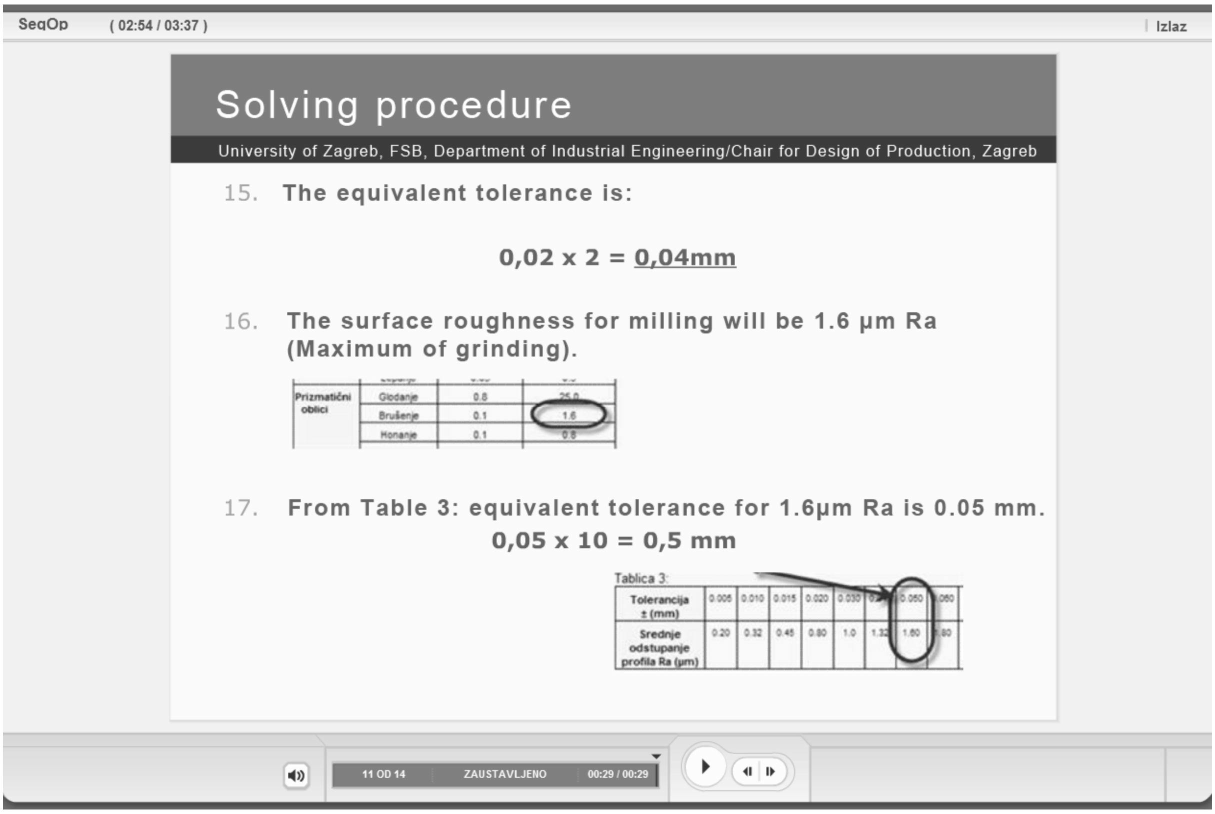
- For the surface marked with bold line (sketch) assign kinds of the technologies (material removal), sequence operation, dimensions of final workpiece, tolerances and surface quality (Ra) for each operation. Use tables 1 – 3!

a= 0,5 Ra; b = 0,0009mm; c = 90mm, d = ± 0,015.

Fig. 4. Example of development sequencing operations



Solving procedure

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15. **The equivalent tolerance is:**

0,02 x 2 = <u>0,04mm</u>

16. **The surface roughness for milling will be 1.6 μm Ra (Maximum of grinding).**

Prizmatični oblici	Glodanje	0.8	25.0
	Brušenje	0.1	1.6
	Honanje	0.1	0.8

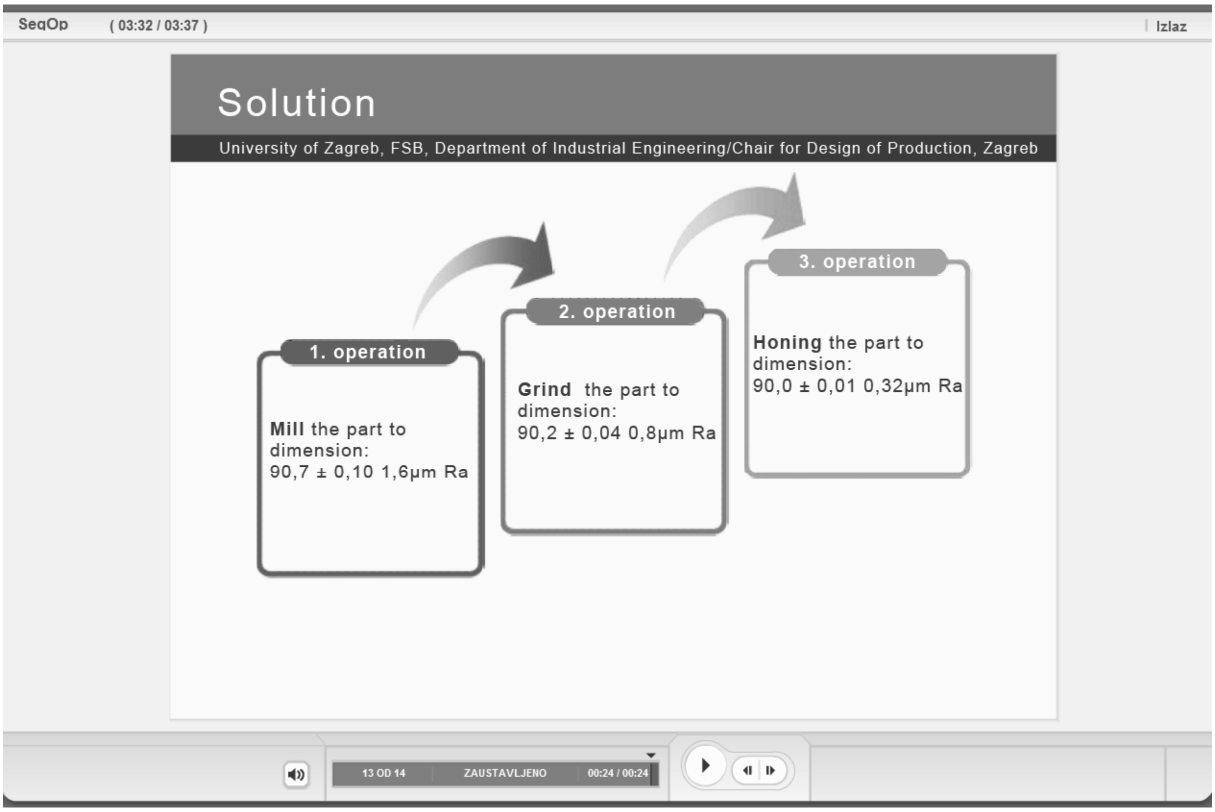
17. **From Table 3: equivalent tolerance for 1.6μm Ra is 0.05 mm.**

0,05 x 10 = 0,5 mm

Tablica 3:

Tolerancija ± (mm)	0.005	0.010	0.015	0.020	0.030	[illegible]	0.050	[illegible]
Srednje odstupanje profila Ra (μm)	0.20	0.32	0.45	0.80	1.0	1.32	1.60	[illegible]

Fig. 5. Determination of tolerance equivalent



Solution

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1. operation

Mill the part to dimension:
90,7 ± 0,10 1,6μm Ra

2. operation

Grind the part to dimension:
90,2 ± 0,04 0,8μm Ra

3. operation

Honing the part to dimension:
90,0 ± 0,01 0,32μm Ra

Fig. 6. Final solution of sequencing operations

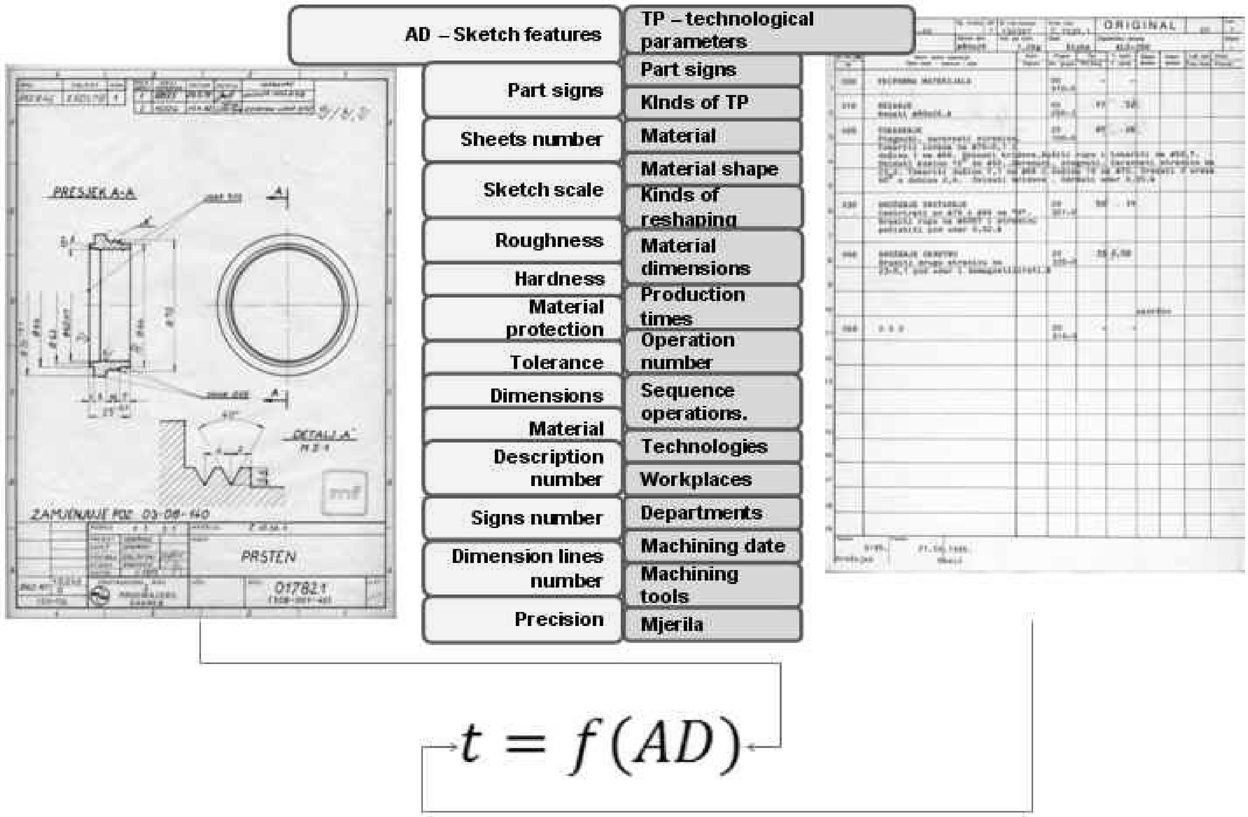


Fig. 7. Connection sketch features with technological date

3. SKETCH FEATURES AND TECHNOLOGICAL DATE – BASE FOR PRODUCTION'S TIMES ESTIMATION

Very frequently (especially in the domain of the SME company) we must answer fast to some important requests for offers, generated for individual or batch production, for example:

1) great number of requested offers for production of products at once,

2) small batches with very rare repetition,

3) frequent changes of priorities during production,

4) short deadlines of delivery,

5) market demands for approaching prices of the individual or batch production near the prices of mass production, etc.

A very important factor for good company competitiveness on the market is technological flexibility.

For a successful company running a business, necessary condition is existence of the process planning for every product in the saleable process and activities of evaluation of requests of potential customers.

It must be stressed that often technological knowledge and the speed of the process planning would be more important than the technological level of equipment, skills and knowledge of people who realize the technology.

So, we can be faced very often in practice by one of the two undesirable cases:

a) great amount of used time for defining the process planning of products without agreement of order for production products,

b) signing an agreement without estimated precise machining times/costs necessary for products manufacturing and realization agreed upon products.

4. DEVELOPMENT OF TECHNOLOGICAL DATEBASE

Basic technological processes must give the requested date to sales department as the most important date for defining product costs/price and deadline of delivery. Also, basic technological processes can be very useful as the base for detailed process planning or optimization of process planning. We can be faced by few approaches in the process planning. For example, definition very precise IF THEN procedure for creation technological knowledge database. Or, we can be faced by use of fuzzy logic and certainties of possible solutions. Or, we can try to solve restricted area of problem by heuristic approach.

What can it means? Technological processes are basically based upon product drawings with adequate dimensions, tolerance (dimensional and geometrical), surface roughness, batch size, shape and kind of material, heat treatment, requested delivery, disposable equipment, tools, etc. At the same time, the process plan gives the primary results of the planner experience, intuition and decision support. Very often, process planners work under a high level of pressure or lack of time.

The process planner can establish possible connections between sketch features and necessary machining times for products manufacturing. The defined hypothesis says that we can express established connections, except methods of AI, with regression equations. The established purpose is to the define the basic process planning with satisfactory precision.

So, the fundamental idea in the fifth approach [7, 8, 9] of production time's estimation is investigation of the existence kind of relationship between the shape and the date from sketch and process type, process sequencing, primary process, way of tightening, selection of tools, machine tools, production times, etc. (Fig. 7).

The greatest challenge is to establish (or investigate) the most important factors from the sketch for useful, easy, fast and very exact estimation of production times. It is necessary in the process of offers definition for better estimation terms of product delivery, production times and costs, manufacturing management and last but not the least important, product price.

As one of the first steps in our project research, we have defined possible shapes of raw material and 30 potential basic technological processes. Parameters of basic technological processes can be:

– shape and kind of raw material (features of sketch, knowledge base),

– type of workpiece (features of sketch, shape and dimensions of raw material),

– necessary operations for treatment (features of sketch, expected production time, knowledge base),

– operations sequencing (features of sketch, necessary operations of treatment, knowledge base),

– necessary production times (features of sketch, based on equations).

So, features of sketch (independent variables), possible dependent variables, size and criteria for sample homogenization (principles of group technology) have to be established for analysis of variance and regression analysis. Relations between tables (Fig. 9) (Marks of parts, Realized technological processes, etc.) are elements of realized technological processes and procedures.

5. PREVIOUS RESEARCH OF ESTABLISHED HYPOTHESIS

As the precedence work we have to define the domain borders of independent variables (less than 40), the reduction number of variables by correlation/factor analysis and the definition type of the smoothing curve with a high index of determination. Of course, the desired level of generalization in the regression analysis would be an important indicator for the quality of the regression equation.

A group of rotational parts with heat treatment (Table 1), as an example of multiple linear regressions (four variables) was selected. The observed multiple linear regression $Y = f(X1, X2, X3, X4)$ (1) has the index of determination R^2 of 0.969211 (Table 2):

$$Y = -30.4632 + 0.000489\,X1 + 7.553821\,X2 + 0.560182\,X3 + 124.5732\,X4] \qquad (1)$$

where is:

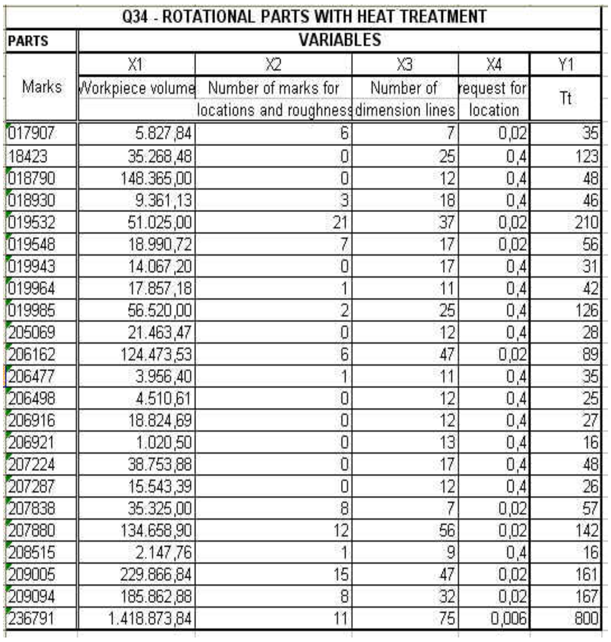
Y = production time
$X1$ = workpiece volume
$X2$ = number of marks for locations and | roughness
$X3$ = number of dimension lines
$X4$ = requests for locations.

Eight multiple linear regression equations were established for a different group of values of parts (the same group) with the significant level of homogeneity. The next steps of research were conducted in the way of automatic recognition and joining the part to the adequate group of the parts (logical operators in database).

The research as the second request has included more precise measurement and calculation production times of parts. As the third request was the procedure for estimation of the multiple linear regression with the least variables, the greatest index of determination and good coincidence calculated and predicted values of the dependent variable.

Table 1

Sample of sketches and features for 4 independent variables and 1 dependent variable



Q34 - ROTATIONAL PARTS WITH HEAT TREATMENT					
PARTS	VARIABLES				
Marks	X1	X2	X3	X4	Y1
	Workpiece volume	Number of marks for locations and roughness	Number of dimension lines	request for location	Tt
017907	5.827,84	6	7	0,02	35
18423	35.268,48	0	25	0,4	123
018790	148.365,00	0	12	0,4	48
018930	9.361,13	3	18	0,4	46
019532	51.025,00	21	37	0,02	210
019548	18.990,72	7	17	0,02	56
019943	14.067,20	0	17	0,4	31
019964	17.857,18	1	11	0,4	42
019985	56.520,00	2	25	0,4	126
205069	21.463,47	0	12	0,4	28
206162	124.473,53	6	47	0,02	89
206477	3.956,40	1	11	0,4	35
206498	4.510,61	0	12	0,4	25
206916	18.824,69	0	12	0,4	27
206921	1.020,50	0	13	0,4	16
207224	38.753,88	0	17	0,4	48
207287	15.543,39	0	12	0,4	26
207838	35.325,00	8	7	0,02	57
207880	134.658,90	12	56	0,02	142
208515	2.147,76	1	9	0,4	16
209005	229.866,84	15	47	0,02	161
209094	185.862,88	8	32	0,02	167
236791	1.418.873,84	11	75	0,006	800

Table 2

Index of determination for ANOVA

Regression statistics	
Multiple R	0.984485
R square	0.969211
Adjusted R square	0.962369
Standard error	31.43457
Observations	23

6. HOMOGENIZATION OF THE SAMPLE, CLASSIFIERS SELECTION AND SIGNIFICANCE OF VARIABLES

The blank material may be expressed by three basic groups: quality, shape and dimensions. The investigation of the connection between the production time and features of the product (through four groups of independent variables) can give the regression equation. All elements of the sample are records for the created database (Fig. 9).

The considered sample consists of original production documentation of one Croatian company for manufacturing machine tools. For establishing potential high quality relationship between features of sketch and production time we have to execute two actions. One action can be explained as exploring measures for the reduction number of independent variables for regression analysis. The method of analysis of variance (ANOVA procedure) and stepwise multiple linear regression (Excel, MatLab) were very helpful in the process reduction of the number of independent variables.

The other action was the process of sample homogenization (Fig. 10) for example, elimination of too big or small value of members of the sample. The shape product dependent variables as the most important criteria were established for 8 different product types. As a result of development we have developed some regression equations. Size samples are results of sample homogenization and query of logical operators (classifiers) for 12 basic technological operations (OTP) (Fig. 8).

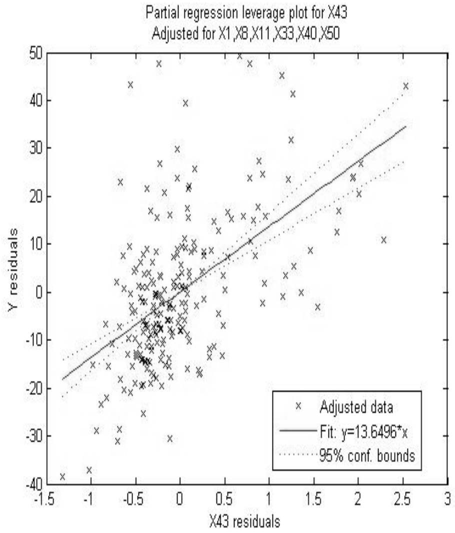


Fig. 8: Partial regression l average plot for X43

7. DEVELOPMENT OF STEPWISE LINEAR MULTIPLE REGRESSIONS

As the precedence work we have to define the domain borders of independent variables (less than 40), the reduction number of variables by correlation/factor analysis and the definition type of the smoothing curve with a high index of determination.

Of course, the desired level of generalization in the regression analysis would be an important indicator for the quality of the regression equation. One of the most important problems was the process of homogenization of the sample of products. The adequate method for this action was one of the methods of group technology.

The logical operators during the query process in database Access (Fig. 9) were very helpful in the process of homogenization of the sample of products. As the result of previous research, as for sample homogenization, classifier selection and multiple stepwise linear regression we obtained: (Fig. 11): *7 independent selected variables, basic sample of 320 parts, constraints for data parts, 8 regression equations,* percentage of explained effects, relative error (7–30%), etc. The other approaches were critical analysis values of dependent variables and excluding the extreme values.

As an example of multiple linear regression (seven variable), after classifiers actions and stepwise multiple regression was selected a group of metal rods with 221 parts in a sample.

The observed multiple linear regression $Y = f(X43, X40, X11, X50, X8, X33, X1)$ (2) has the index of determination $R^2 = 0.742471$ for X43 residuals (Fig. 8):

Y = machining time,

$X1$ = tolerance external diameter of workpiece,

$X8$ = surface roughness,

$X11$ = internal diameter of workpiece,

$X33$ = ratio length/diameter of workpiece,

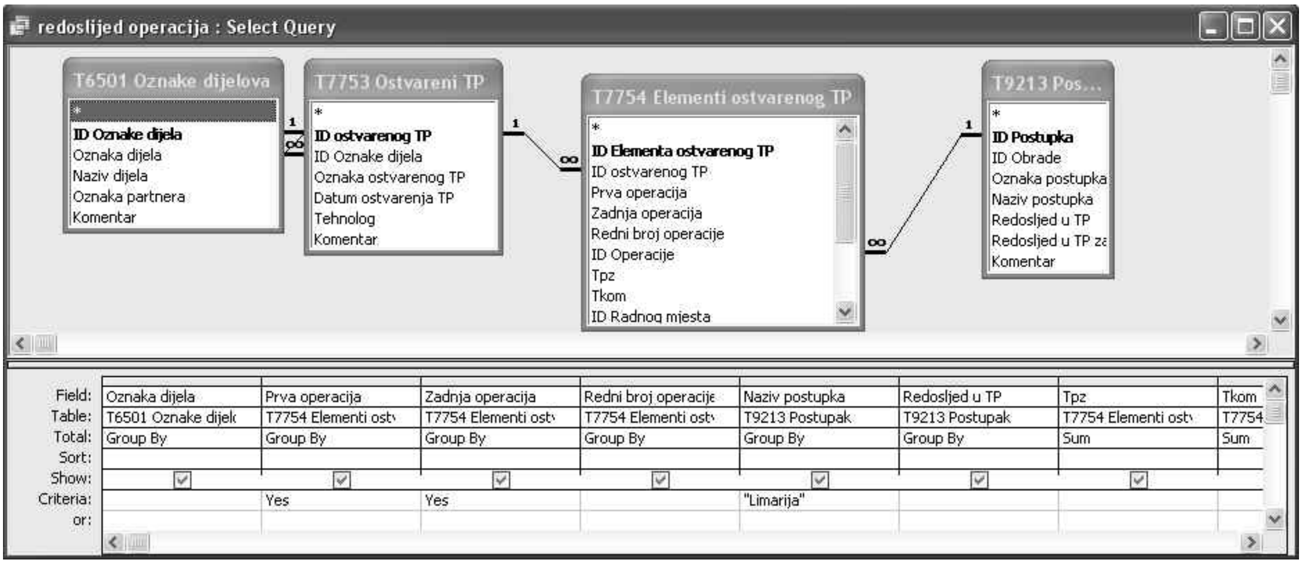
$X40$ = complexity of workpiece,

$X43$ = superficial area of raw material,

$X50$ = difference of length workpiece and raw material,

$$Y = 36.419 + 13.649\,X43 + 0.099\,X40 + 0.459\,X11 + 2.023\,X50 - 4.080\,X8 - 0.655\mathrm{X33} + 0.712\,X1 \tag{2}$$

Eigth multiple linear regression equations were established for a different group of values of parts (the same group) with the significant level of homogeneity.



Field:	Oznaka dijela	Prva operacija	Zadnja operacija	Redni broj operacije	Naziv postupka	Redosljed u TP	Tpz	Tkom
Table:	T6501 Oznake dijel	T7754 Elementi ost	T7754 Elementi ost	T7754 Elementi ost	T9213 Postupak	T9213 Postupak	T7754 Elementi ost	T7754
Total:	Group By	Group By	Group By	Group By	Group By	Group By	Sum	Sum
Sort:								
Show:	☑	☑	☑	☑	☑	☑	☑	
Criteria:		Yes	Yes		"Limarija"			
or:								

Fig. 9. Relation database [7]

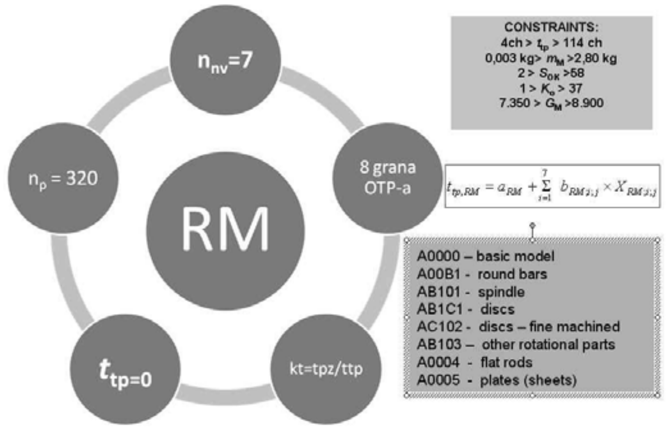


Fig. 10. Regression models

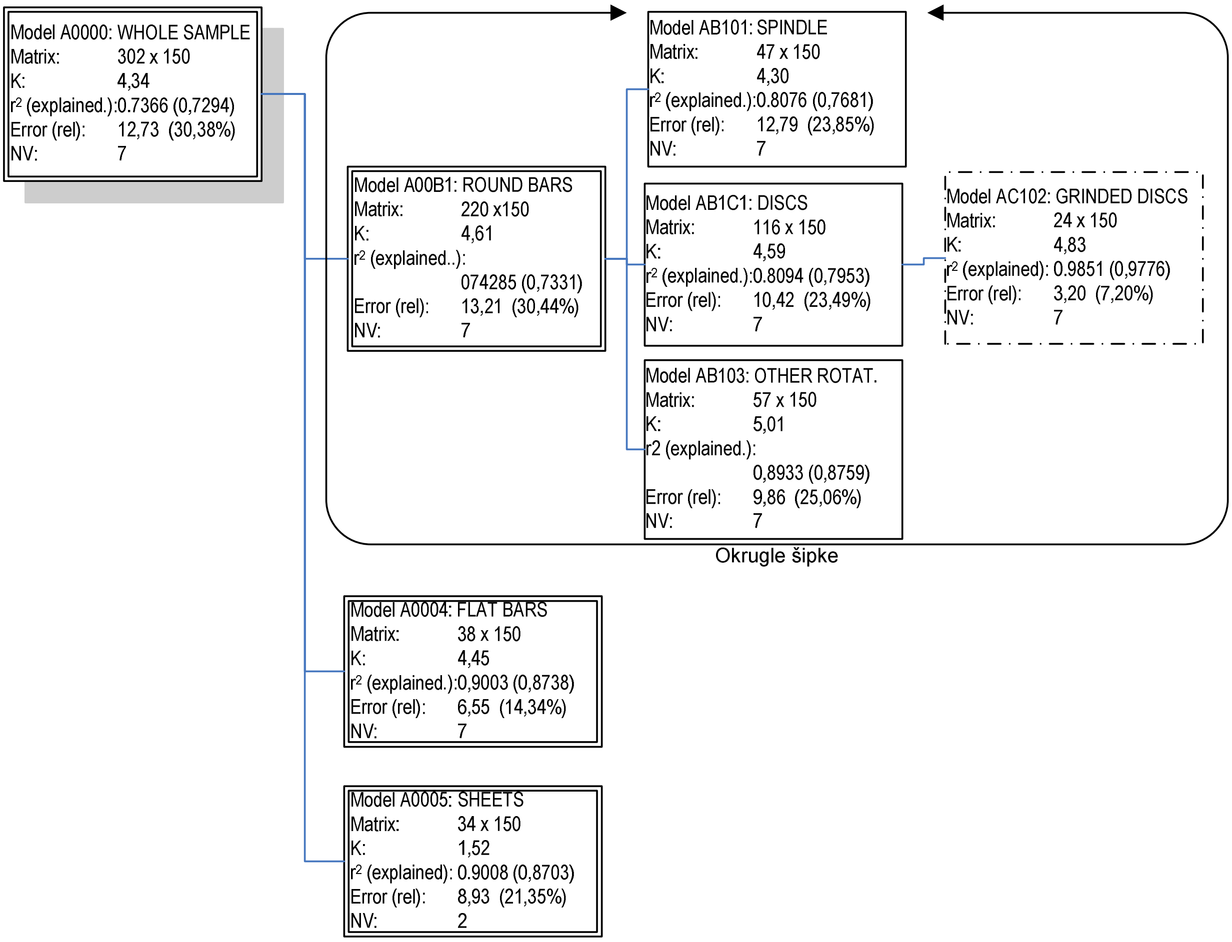


Fig. 11. Result of classifiers activities in technological knowledge base [7]

8. CONCLUSION

Hypothesis about relationship on one hand between sketch features and on the other hand production times and parameters of technological processes is confirmed. The result of the research is the fact that a possible initial shape of material raw can be automatically defined on the base of the sketch features.

The process of the previous classification parts in defined types of parts based primarily on geometric features is not so important in the process planning. Solution can, not be found in determination type of the part but in the parts joining to a specific, in advance, type of defined fundamental technological processes (OTP) based on sketch features and selected classifiers.

The logical operators during the query process in database Access were very helpful in the process of homogenization of the sample of products.

For establishing potential high quality relationship between features of sketch and production time we have to execute two actions.

One action can be explained as exploring measures for a reduction number of independent variables for the regression analysis. The method of analysis of variance (ANOVA procedure) and the stepwise multiple linear regression (Excel, MatLab) were helpful in the process reduction number of independent variables.

The other action was the process of sample homogenization, for example, elimination of too big or small value of sample members. Shape products as the most important criteria were established for 8 different product types. The results of classifiers activities in technological knowledge base are: 8 recognized homogeneous groups of parts, 7 independent different variables, high percentage of explained effects, relative error (7–30%), etc.

As a result of the development we have developed 8 regression equations. The size samples are results of sample homogenization and .query of logical operators (classifiers) for 12 basic technological operations (OTP).

Research work would continue by developing user friendly web application for estimation production times, looking for an adequate model for optimization (minimum of production time, maximum occupied capacity, maximum profit for assortment of selected products), etc. Implementation of the genetic algorithm can be one of the possible methods for solving optimization problems.

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REFERENCES

[1] http://ptp.fsb.hr

[2] N. Volarević, P. Ćosić: Improving process planning through sequencing the operations, *AMST'05,CISM Courses and Lectures* – No. 486 , Springer Verlag, Wien New York, 2005, pp. 337–347.

[3] N. Volarević, P. Ćosić: Shape Complexity Measure Study, *DAAAM 2005*, Opatija, Croatia, 2005, pp. 375–376.

[4] P. Ćosić, A. Levanić: W*eb oriented database system for process planning*, Pacific Congress on Manufacturing and Management, PCMM) 2004, 8–10 December 2004, Gold Coast, Australia, ISBN 0-9578296-1-2, 2004, pp. 922–928.

[5] J. Balić,, I. Veza, F. Čuš: *Advanced Production Technologies* (in Croatian & Slovenian language), FESB, Split & Faculty for Mechanical Engineering, Maribor, 2007, Chapter 4. P. Ćosić, Process Planning in Web Environment, ISBN 86-435-0777-6; 2007, pp. 59–97.

[6] P. Ćosić, D. Antolić, I. Milić: Web Oriented Sequence Operations, *19th International Conference on Production Research*, ICPR-19, July 29 – August 2, 2007, Valparaiso, Chile, CD.

[7] D. Antolić: *Estimation of Production Times of Products by Help of Regression Models*, Master's thesis, defended 27 April 2007, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, 2007.

[8] P. Ćosić, D. Antolic: *Fast Process Planning – One of the Criteria for Better Competitiveness*, Global Conference on Production and Industrial Engineering (CPIE-2007), 22 – 24th March, 2007, Jalandhar, Punjab, 144011, India, CD.

[9] P. Ćosić, D. Antolić: *Features of the sketch – Base for the Fast Process Planning*, PSU-UNS International Conference on Engineering and Environment – ICEE 2007, Phuket, Thailand, May 10–11, 2007, CD.

[10] V. Gečevska, F. Čuš, V. Dukovski: Modeling of Manufacturing Activities by Process Planning Knowledge Representation, *International Journal of Simulation Modeling*, ISSN 1726-4529, Vol. **5**, No. 2, June 2006, pp. 69–81.

[11] Gečevska V.: Computer Aided Process Planning, Chapter V in Scientific monography *Intelligent Manufacturing Systems*, 2007, ISBN 978-9989-2701-0-9, pp. 131–150, COBBIS.MK-ID 69210890

Резиме

ЗАБРЗАНО ПРЕСМЕТУВАЊЕ НА ПРОИЗВОДНО ВРЕМЕ КАКО ОДЛУЧУВАЧКА ПОДДРШКА НА ВРЕМЕТО ЗА ИСПОРАКА И НА ПРОИЗВОДНИТЕ ТРОШОЦИ

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Клучни зборови: забрзано проектирање на технолошки процеси; технолошка база на знаење; повеќекратна линеарна регресија

Современите пазарни услови ја детерминираат потребата од брз одговор на барањата од клиентите за понуди генерирани на поединечно или малосериско производство, како што се на пример, голем број барања за производство на одделни производи со мала можност за повторување, динамични измени на приоритетите во текот на производството, кратки рокови за испорака, следење на барањата на пазарот во однос на цените итн. Во истражувањето прикажано во овој труд е предложена можна конекција помеѓу основни облици од кои се моделираат фамилии на производи и производното време за изработка на производите, при што како резултат е генерирана технолошка база на знаења.