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INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

ON FLOW PARAMETERS OF NORMAL SHOCK WAVES IN SATURATED STEAM

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The paper deals with solution of parameters of saturated water steam flow at occurrence of a normal shock wave. Solution is based on balances of mass, momentum, energy and the state equations of steam according to the International Association for Properties of Water and Steam – IAPWS-IF97. The calculation is using an iterative procedure to solve parameters of superheated steam downstream of the normal shock wave. Finally the values of velocity of steam flow are solved and data for analysis and discussion are prepared.

Keywords: Shock wave, Saturated Steam, Iterative procedure, IAPWS-IF97

Introduction

A classical task of gas dynamics is a derivation and solution of relations of normal shock wave in an ideal gas, e.g. [1]. The system of basic equations for balances of mass, momentum and energy together with state equation of an ideal gas leads to derivation of well-known Rankine-Hugoniot relations, relations between state quantities and Mach number upstream of the normal shock wave, and popular Prandtl relation for non-dimensional velocities upstream and downstream of the normal shock wave. For practical purposes these relations are solved in Aerodynamic Calculator [2]. Above mentioned knowledge on parameters of normal shock waves in an ideal gas has limited possibilities for application in the case of water steam as the flow medium. For calculations of shock wave parameters in steam it is recommended to take the equation of state for steam according to documents by International Association for Properties of water and Steam (IAPWS). Namely formulation dependence of pressure p, specific volume, and enthalpy h according to the IAPWS-IF97 [3] should be accepted.

Calculation procedure for solution of thermodynamic parameters of superheated water steam downstream of the normal shock wave occurring in saturated steam was derived in contribution [4]. It was proved that steam can be considered to be an ideal gas only for pressure less then $p \approx 0.01$ MPa and for very weak shock waves. For higher steam pressures, parameters of steam downstream of the normal shock wave are considerably different from the case of assumption for steam to be an ideal gas. Another knowledge for conditions of high-pressure steam (near critical parameters (p_{crit} = 22.064 MPa)) is a very complex course of dependences of resulting parameters. It was proved to be very convenient to abandon dependences on Mach number but to accept dependences on ratio of static pressures downstream and upstream of the normal shock wave.

In this paper the results of calculation will be focused to values of velocities upstream v_1 in saturated steam and downstream v_2 of the normal shock wave in superheated steam. Solution will be performed in full parameters of saturated steam from triple point (p_{tr} = 0.000611657 MPa) to critical point (p_{crit} = 22.064 MPa).

2. Shock wave in saturated steam

A Theoretical approach to solution of parameters on a normal shock wave is based on balance equations for steam passing the infinitesimally thin control volume on shock wave (Fig.1). The modified balance equations are:

Balance of mass $$\frac{\dot{m}}{A} = \rho_1 v_1 = \rho_2 v_2 \tag{1}$$

Balance of momentum $$p_1 - p_2 = \frac{\dot{m}}{A}(v_2 - v_1) \Rightarrow p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2 \tag{2}$$

Balance of energy $$h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2} = h_{01} = h_{02} = h_0 \tag{3}$$

Equation of state (IF-97 [3]) $$\frac{1}{\rho} = f_{v\_ph}(p, h) \tag{4}$$

where $\dot{m}$ is mass flow, A is cross section of the control volume, ρ is density, v is velocity, p is pressure, h is enthalpy; indices $_1$ is upstream of the shock wave, $_2$ is downstream of the shock wave, $_0$ is total value.

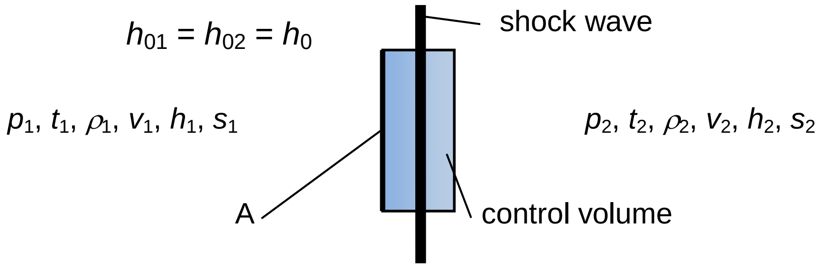

Fig.1: The scheme of a shock wave, control volume, and parameters on a normal shock wave.

All thermodynamic parameters upstream of the shock wave are given. In this study they are parameters of saturated steam. In the paper [4], the calculation procedure for given pressure downstream of the shock wave p_2 (when $p_2 > p_1$) was derived. The iterative procedure is based on the modified equations (1) to (3) and on the chosen value of density downstream of the shock wave $\rho_2^{(1)}$ in first iterative step:

$$h_2^{(n+1)} = h_1 + \frac{1}{2}\left(\frac{1}{\rho_1} + \frac{1}{\rho_2^{(n)}}\right)(p_2 - p_1) \ , \tag{5}$$

where index $^{(n)}$ denotes n-th iteration step. After application of equation of state (4) value of density downstream of the shock wave is solved:

$$\rho_2^{(n+1)} = \frac{1}{f\left(p_2, h_2^{(n+1)}\right)} \tag{6}$$

The solved value of density downstream of a shock wave $\rho_2^{(n+1)}$ is used in next (n + 1)-th iteration step into the equation (5). It was proved that the iterative procedure is relatively fast and in the paper [4] solved thermodynamic parameters on a normal shock wave in all region of saturated steam are presented in comparison with the case of steam considered to be an ideal gas. In the Fig.2, phase diagram (pressure p - temperature t) shows dependences of parameters of supersaturated steam downstream of normal shock waves in saturated steam for $\frac{p_2}{p_1}$ = const. Thermodynamic parameters are also presented in diagram in Fig.3 (enthalpy h - entropy s) as dependences for $\frac{p_2}{p_1}$ = const. The calculation offers solutions of other parameters.

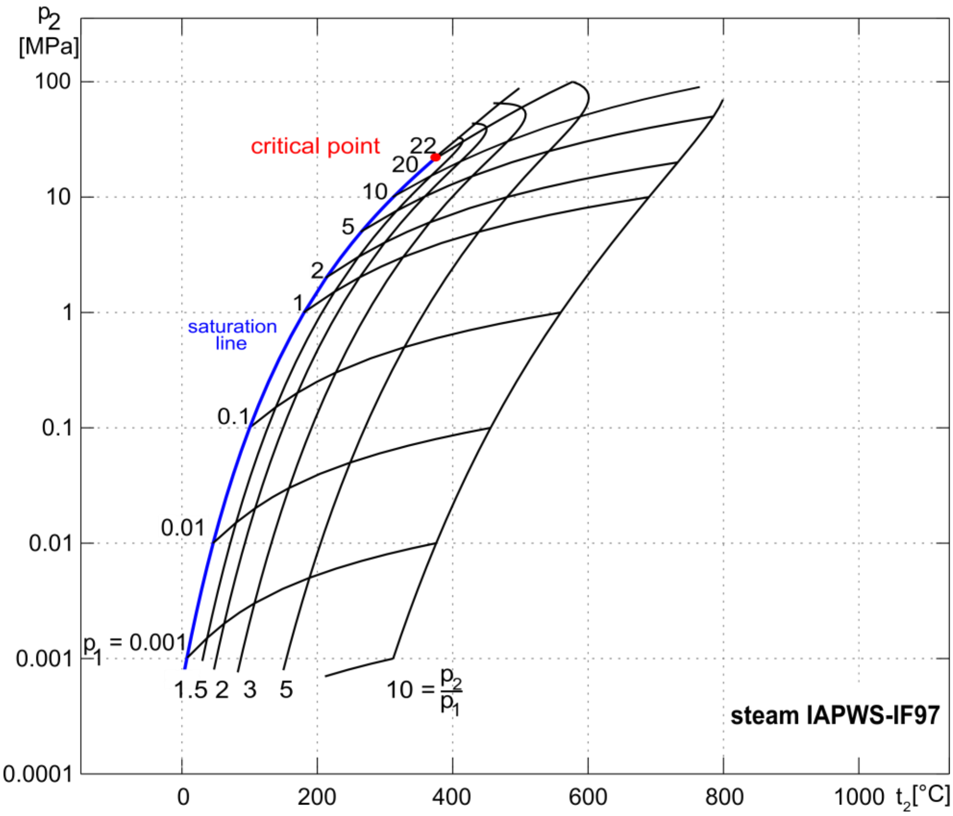

Fig.2: State parameters downstream of normal shock waves in saturated steam p_1/p_2 = const. lines

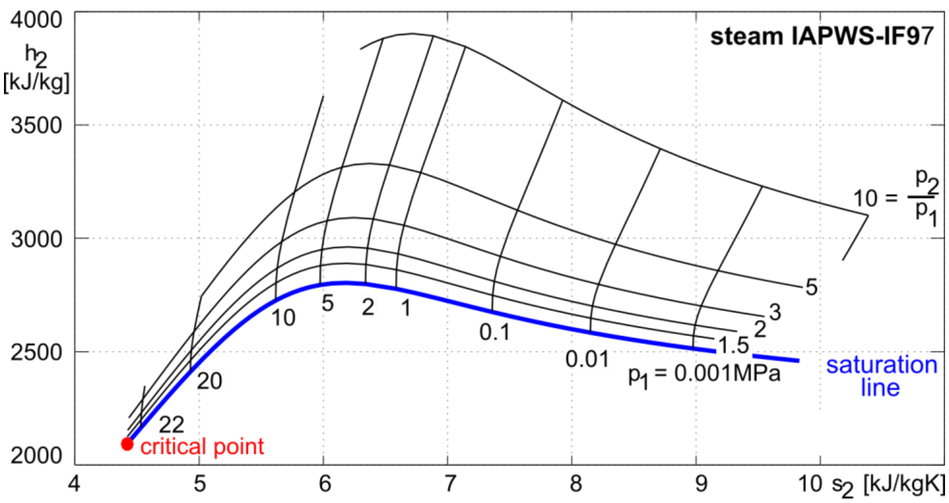

Fig.3: State parameters downstream of normal shock waves in saturated steam p_1/p_2 = const. lines

3. Velocities of saturated steam upstream of the normal shock wave

3.1. Resulting velocities of superheated steam downstream of the shock wave

For given thermodynamic parameters of saturated steam upstream of a normal shock wave and given static pressure downstream of the shock wave p_2, enthalpy h_2 downstream of the shock is solved using the iterative procedure described in Sect.2. There is no problem to solve velocity v_1 of saturated steam upstream of the normal shock wave according to relation

$$v_1 = \frac{\dfrac{p_2 - p_1}{\rho_1}}{\sqrt{2\dfrac{p_2 - p_1}{\rho_1} - 2(h_2 - h_1)}}, \tag{7}$$

which is derived from equations (1) to (3). Velocity v_2 downstream of the normal shock wave is solved according to relation

$$v_2 = v_1 - \frac{p_2 - p_1}{\rho_1 v_1}, \tag{8}$$

which is derived from equations (1) and (2). Achieved results from calculations in all region of parameters of saturated steam are introduced in Fig.4 as dependencies for p_2/p_1 = const.

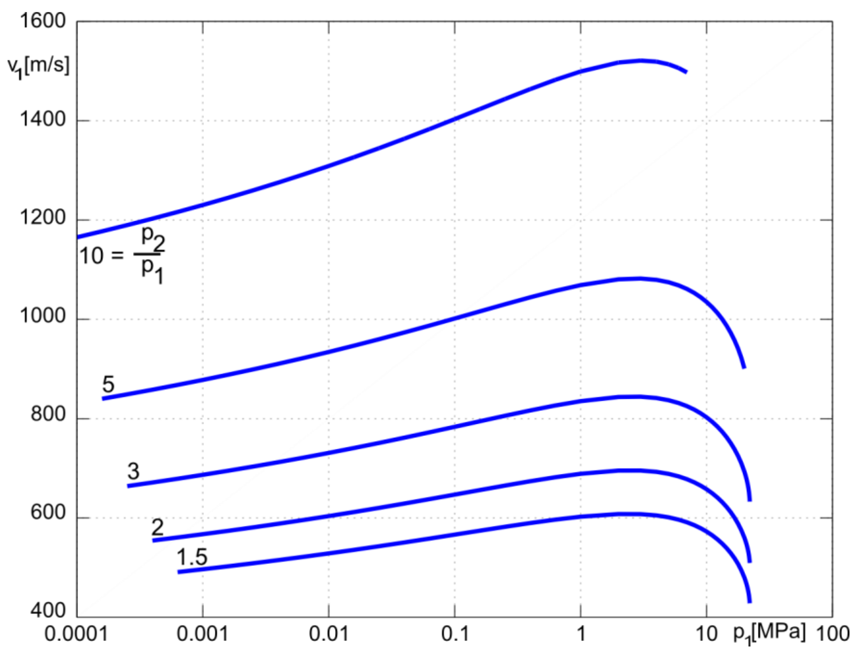

Fig.4: Dependencies of velocities v_1 on p_1 on a normal shock wave in saturated steam for p_2/p_1 = const.

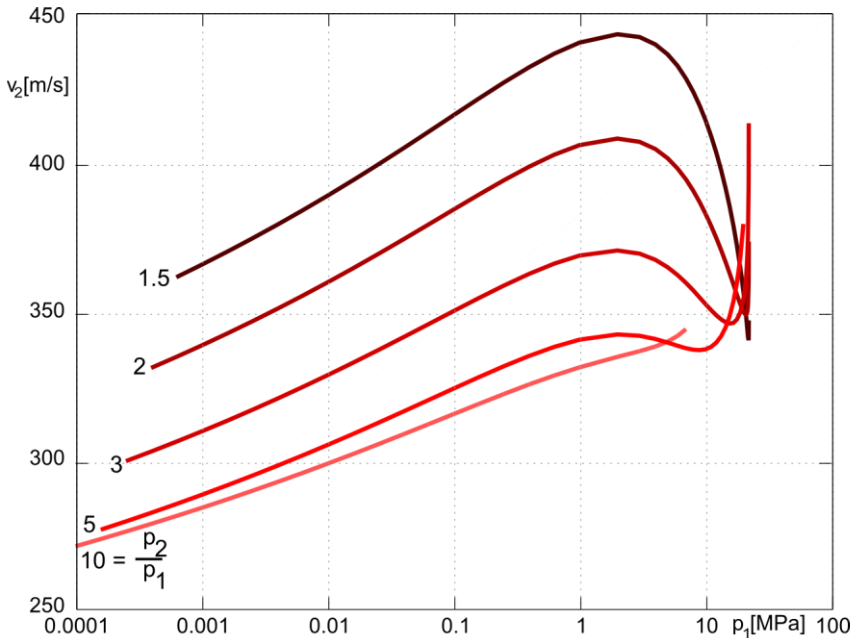

Fig.5: Dependencies of velocities v_2 on p_1 on a normal shock wave in saturated steam for p_2/p_1 = const.

3.2. Iterative procedure for given upstream velocity

There can be derived another iterative procedure for solving the thermodynamic parameters of superheated steam downstream of a normal shock wave for given thermodynamic parameters upstream of the normal shock wave and for given velocity upstream of the shock wave v_1, so that $v_1 > a_1''$ (where a_1'' is the speed of sound in saturated steam upstream of the shock wave).

Density $\rho_2^{(1)}$ is chosen in first iterative step. The iterative procedure is based on modified equations (1) to (3):

$$p_2^{(n+1)} = p_1 + \rho_1 v_1^2 \left(1 - \frac{\rho_1}{\rho_2^{(n)}} \right) \tag{9}$$

$$h_2^{(n+1)} = h_1 + \frac{v_1^2}{2} \left(1 - \frac{\rho_1^2}{\left(\rho_2^{(n)}\right)^2} \right) \tag{10}$$

Using equation (4) the density is solved:

$$\rho_2^{(n+1)} = \frac{1}{f\left(p_2^{(n+1)}, h_2^{(n+1)}\right)} \tag{11}$$

The solved value of density downstream of a shock wave $\rho_2^{(n+1)}$ is used in next (n + 2)-th iteration step into the equations (9) and (10). The iterative procedure is under further investigation. Solved thermodynamic parameters enable to determine values of other thermodynamic parameters of superheated steam downstream of the shock wave according to the IAPWS-IF97 standard as well as velocity v_2 of superheated steam downstream of the shock wave according to equation (8). In Fig.6 dependencies of state parameters downstream of the shock wave are depicted in the phase diagram (pressure p – temperature T) for v_1 = const. Thermodynamic parameters are also presented in diagram in Fig.7 (enthalpy h - entropy s) as dependences for v_1 = const.

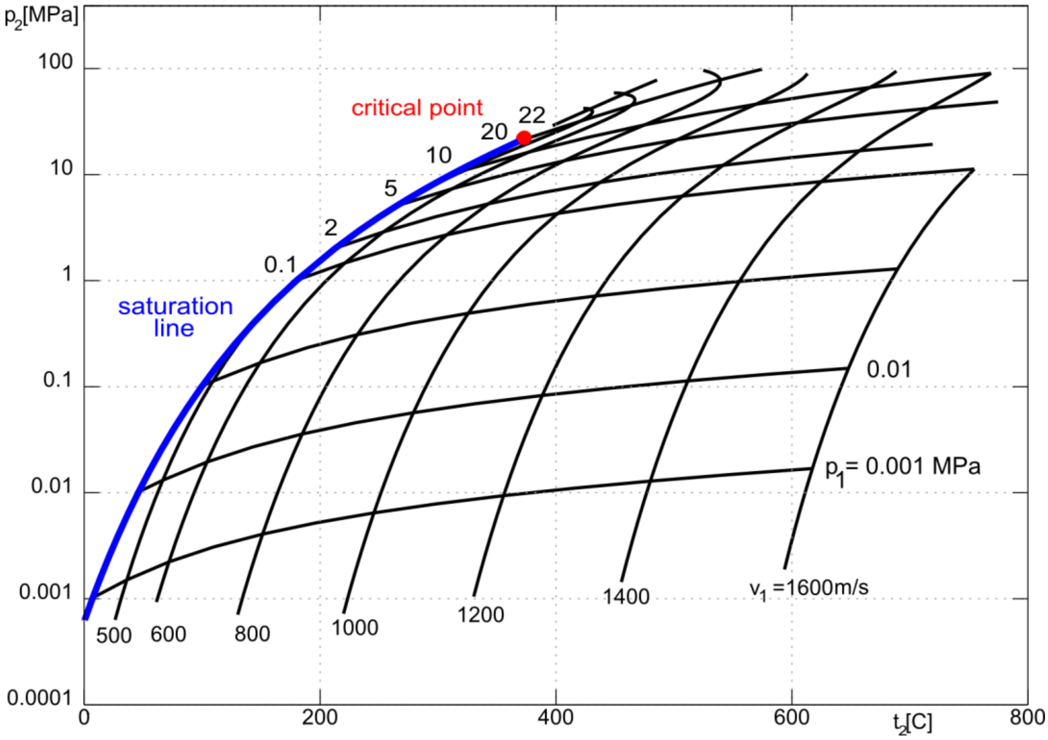

Fig. 6: State parameters downstream of normal shock waves in saturated steam, v_1 = const.

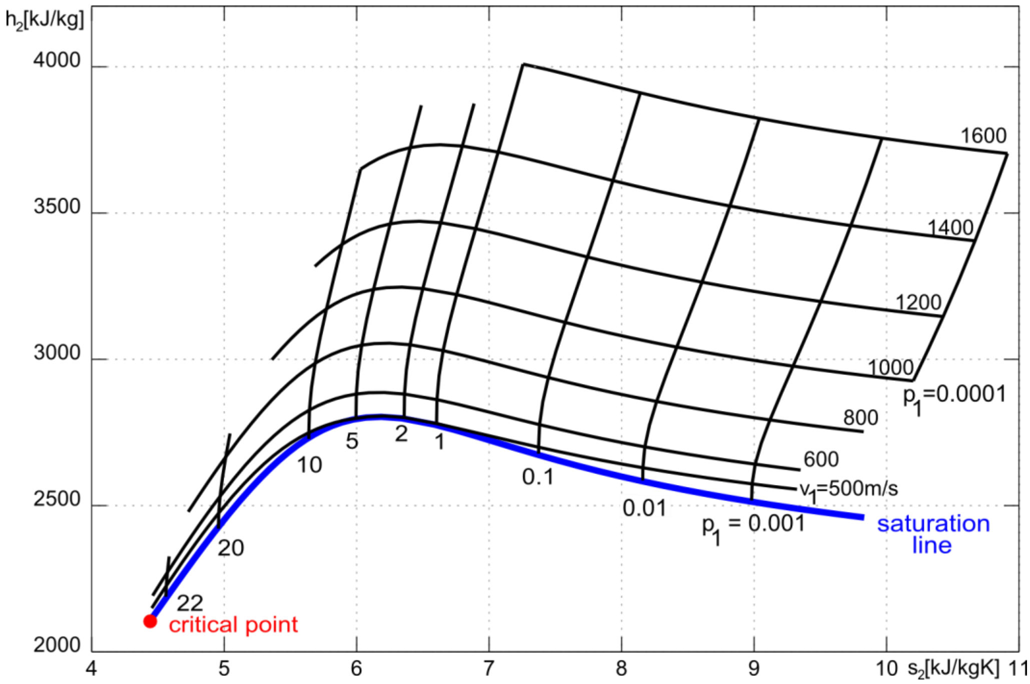

Fig. 7: State parameters downstream of normal shock waves in saturated steam, v_1 = const.

3.3. Enthalpy to velocities product ratio

Total enthalpy h_0 can be solved from equation (4). Total enthalpy is the maximal energy of steam flow and remains constant in shock waves.
It is convenient to show a quantity defined as ratio of total enthalpy and product of velocities upstream and downstream of a normal shock wave:

$$\frac{\tilde{h}_0}{v_1 v_2} \tag{12}$$

In the theory of ideal gas this quantity has value

$$\frac{\tilde{h}_0}{v_1 v_2} = \frac{1}{2}\frac{\kappa+1}{\kappa-1} = const., \tag{13}$$

where κ is ratio of heat capacities and $\tilde{h}_0$ is enthalpy which has the zero value at total temperature equal to zero (0 K). Transformed enthalpy $\tilde{h}_0$ for water steam is

$$\tilde{h}_0 = h_0 - \Delta h \ , \tag{14}$$

where Δh = 1990.273 kJ/kg. The quantity $\frac{\tilde{h}_0}{v_1 v_2}$ has not for normal shock waves in saturated steam a constant value. Its course is shown in diagram in Fig.8 as dependencies on static pressure p_1 and static pressure ratio p_2/p_1.

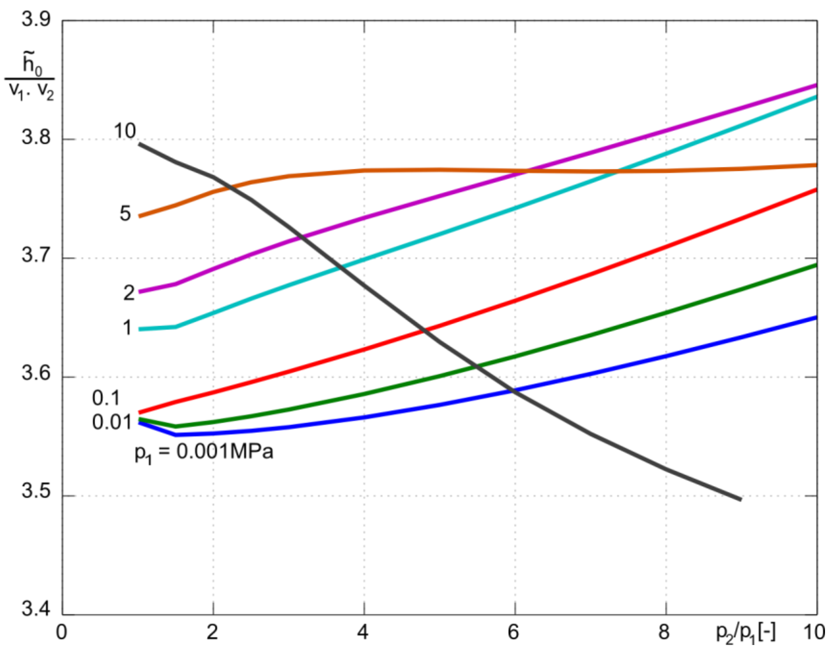

Fig. 8: Values of quantity $\frac{\tilde{h}_0}{v_1 v_2}$ for normal shock waves in saturated steam.

Conclusion

Two iterative procedures are developed for solution of quantities of superheated steam downstream of a normal shock wave in saturated steam. They are based on physical model of normal shock wave by means of balances of mass, momentum, and energy and by mean of the dependence of state quantities of steam according to the document of the International Association for Properties of Water and Steam – IAPWS-IF97. Calculation procedures will be applied at further physical models and at solution of flow fields in water steam for research, design and operation of steam turbines of large output.

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