

MODEL OF STEAM-WATER INJECTOR

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ABSTRACT

Two-phase steam-water injectors may be applied as a feeding pump device or as a condensing device in many applications. In such injectors steam is a motive fluid while cold water is a secondary fluid. One-dimensional model of two-phase injector has been proposed in the paper. Model is based on two-fluid model of two-phase flow along with a set of closure equations. The results of calculations have been compared with experimental results showing reasonably good agreement.

INTRODUCTION

Steam –water two-phase injector investigated in the present paper consists of motive steam nozzle, water nozzle, mixing chamber and diffuser. Two different kinds of such injector may be distinguished with respect to the arrangement of the steam nozzle: with a central or outer (annular) nozzle. Figure 1 shows a schematic sketch of the injector with the central arrangement of the steam nozzle which will be investigated in the paper. In this case steam is a motive fluid while water is a secondary fluid.

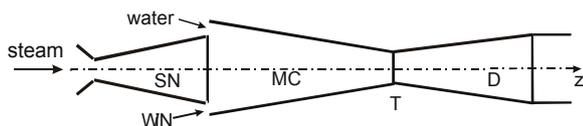


Fig. 1. Schematic sketch of steam-water injector: SN – steam nozzle, MC – mixing chamber, D - diffuser, T- throat, WN – water nozzle.

Having a converging-diverging nozzle shape, the steam is accelerated to the supersonic velocity at the inlet to the mixing chamber. Transfer of heat, momentum (due to the temperature and velocity differences) and mass (due to condensation of steam on water) occur in the mixing chamber. Usually the condensation process is terminated at the throat, followed by a rapid increase of pressure in this region called the shock wave. Then, water is decelerated in the diffuser, which causes a further increase of pressure.

It is seen that the steam injector can be simultaneously used as a water pump and/or a heat exchanger. The exemplary applications of such injector are presented in Fig. 2. The injector can be used as a pumping device in safety passive systems in nuclear power

stations (Fig. 2a) in order to deliver cooling water to the reactor under breakdown conditions. The other possible application is shown in Fig. 2b where the injectors are used as a feedwater heaters, i.e. as a condensing devices (mixing condensers). Details concerning such applications can be found in papers by Cattadori [5] and Narabayasi [7].

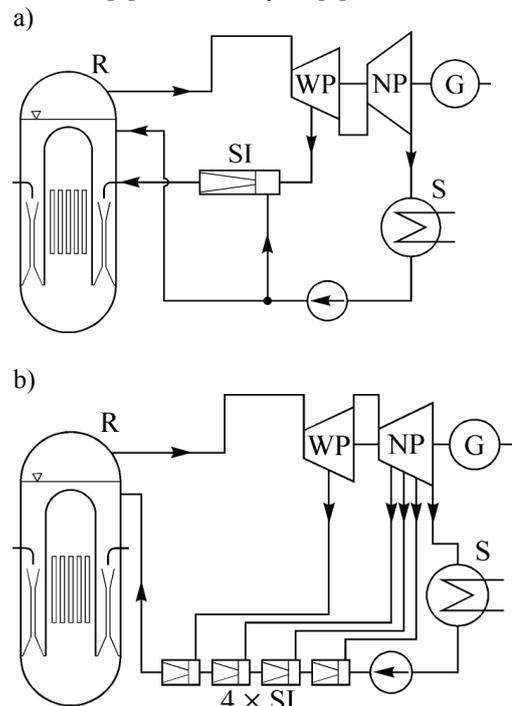


Fig. 2. Exemplary applications of two-phase injectors in nuclear power systems: a) as a cooling water feeding device; b) as a feedwater heating device; R – nuclear reactor; WP – high pressure turbine; NP – low-pressure turbine; S – condenser; G – electric generator.

In many applications of two-phase injector in power generation systems dedicated codes are used to calculate the injector, e.g. RELAP, TRAC, CATHARE – see papers by Pokharna [8]; Carlson [4], Bestion [1]. Various models of two-phase flow are used in order to describe operation of component of power generation systems, mainly: homogenous based on three equations of conservation of mass, energy, and momentum, and two-fluid models based on six equations of conservation for both phases with interphase transport equation, see Ishii [8].

If physical description of the flow is considered, most interesting parts of the steam injector are mixing chamber and diffuser, namely the parts comprising two-phase flow and shock wave region. It should be noted that at present discussion on the physical phenomena taking place there is far from consensus. Even the sequence of flow patterns in mixing chamber is still in dispute. Experimental investigations of steam injector with transparent mixing chamber [2,12] shed more light on this problem. Therefore, it is considered that in the mixing chamber of the steam injector investigated, the following flow patterns (shown schematically in Fig. 3) appear:

- I. separated flow:
 - a) annular – in the first part of the region,
 - b) annular-droplet or annular-mist with vapour as continuous phase and droplets as dispersed phase – in the second part of the region;
- II. homogeneous flow of bubbly structure with vapour bubbles surrounded by the liquid.

Separated flow ends close to the outlet from mixing chamber and transforms into droplet flow close to the throat. Then, the structure changes to bubbly flow. In this region, strong compression is observed inside a shock wave.

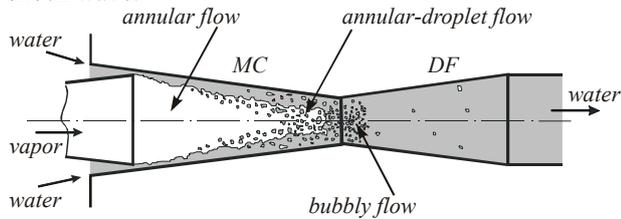


Fig. 3. Flow patterns observed in steam injector.

Looking closer at the region I of separated flow, the following physical processes can be pointed out: acceleration of liquid film, vapour condensation on the film surface, droplet entrainment, droplet deposition, liquid film break-up. Condensation process in the MC is comparatively complex due to simultaneous change of flow patterns. Moreover, the process is complicated by another phenomena, namely the droplet entrainment from film surface and their later deposition back on the film or on the channel wall. These phenomena are observed after the flow in liquid film had developed which requires a certain length for formation of velocity and temperature profiles inside the film. The surface of fully developed film becomes wavy which, subsequently, leads to entrainment of droplets from and deposition on the film.

MODEL ASSUMPTIONS

The present paper deals with modelling of two-phase supercritical injector. Two-fluid steady-state model of two-phase flow has been applied for the injector along with closure equations based on the so-called WAHA-3 code equations [11].

The following general assumption has been applied:

- model is steady state;
- all parameters may be averaged through the cross-section area of low, i.e. one dimensional model is applied;
- vapour phase is saturated;
- liquid phase is subcooled.

Moreover, separated flow model have been applied for the closure equations describing the following model quantities: CVM – virtual mass, S – stratification parameter, C_i – interphase shear stress, F_{wall} – flow resistance at the wall. The closure equations of the WAHA-3 code have been used in our calculations [11].

FORMULATION OF THE MODEL

The model of the two-phase stream-water supercritical injector is formulated below. This model consists of the following conservation equations:

- a) mass conservation for gas phase:

$$\frac{d}{dz}(A\rho_g v_g \alpha) = A\Gamma \quad (1)$$

- b) mass conservation for liquid phase:

$$\frac{d}{dz}(A\rho_l v_l (1-\alpha)) = -A\Gamma \quad (2)$$

- c) momentum conservation for gas phase:

$$\begin{aligned} & \frac{d(A\alpha\rho_g v_g^2)}{dz} + A\alpha \frac{dp}{dz} + \\ & A \cdot C_{VM} \left(v_l \frac{dv_g}{dz} - v_g \frac{dv_l}{dz} \right) + A p_i \frac{d\alpha}{dz} = \\ & = A\alpha\rho_g g \cos\theta - AC_i |v_r| v_r + A\Gamma v_i - AF_{g,wall} \end{aligned} \quad (3)$$

- d) momentum conservation for liquid phase:

$$\begin{aligned} & \frac{d(A(1-\alpha)\rho_l v_l^2)}{dz} + A(1-\alpha) \frac{dp}{dz} - \\ & A C_{VM} \left(v_l \frac{dv_g}{dz} - v_g \frac{dv_l}{dz} \right) - A p_i \frac{d\alpha}{dz} = \\ & = A(1-\alpha)\rho_l g \cos\theta + AC_i |v_r| v_r - A\Gamma v_i - AF_{l,wall} \end{aligned} \quad (4)$$

- e) energy conservation for liquid phase:

$$\begin{aligned} & \frac{d(A(1-\alpha)\rho_l e_l v_l)}{dz} + \frac{d(A(1-\alpha)pv_l)}{dz} = \\ & A Q_{li} - A\Gamma \left(h_l + \frac{v_l^2}{2} \right) + A(1-\alpha)\rho_l g v_l \cos\theta \end{aligned} \quad (5)$$

In conservation equation for liquid phase e_l is the sum of specific internal energy and kinetic energy:

$$e_l = h_l - \frac{p}{\rho_l} + \frac{v_l^2}{2} \quad (6)$$

It is important to note, that vapour is saturated. Because of relation between temperature and pressure under saturated state: $T_s = f(p)$, $T_g = T_s$, there is one independent variable less. Therefore, in this case five conservation equations have been used. The following vector of the state variables is proposed for considered case of the ejector:

$$\varepsilon = (\alpha, p, v_g, v_l, h_l)^T \quad (7)$$

The further simplifications are possible in the particular case of the ejector. We have assumed that vapour phase is always saturated, therefore:

$$\rho_g = \rho_g(p, x = 0) \quad (8)$$

Liquid phase may be treated as incompressible. Taking into consideration above additional assumption the following set of conservation equations have been developed:

a) mass conservation for gas phase:

$$A\rho_g v_g \frac{d\alpha}{dz} + Av_g \alpha \frac{d\rho_g}{dp} \frac{dp}{dz} + A\rho_g \alpha \frac{dv_g}{dz} = \quad (9)$$

$$A\Gamma - v_g \alpha \rho_g \frac{dA}{dz}$$

b) mass conservation for liquid phase:

$$A\rho_l(1-\alpha) \frac{dv_l}{dz} - Av_l \rho_l \frac{d\alpha}{dz} = \quad (10)$$

$$- A\Gamma - v_l \rho_l(1-\alpha) \frac{dA}{dz}$$

c) momentum conservation for gas phase:

$$A\alpha \left(v_g^2 \frac{d\rho_g}{dp} + 1 \right) \frac{dp}{dz} + (Av_g^2 \rho_g + Ap_i) \frac{d\alpha}{dz} + \quad (11)$$

$$(2Av_g \alpha \rho_g + AC_{vm} v_l) \frac{dv_g}{dz} - AC_{vm} v_g \frac{dv_l}{dz} =$$

$$Ag\alpha \rho_g \cos \theta - v_g^2 \rho_g \alpha \frac{dA}{dz} - AF_{g,wall} - AC_i |v_r| v_r + Av_i \Gamma$$

d) momentum conservation for liquid phase:

$$A(1-\alpha) \frac{dp}{dz} - (Av_l^2 \rho_l + Ap_i) \frac{d\alpha}{dz} - \quad (12)$$

$$AC_{vm} v_l \frac{dv_g}{dz} + (2Av_l \rho_l(1-\alpha) + AC_{vm} v_g) \frac{dv_l}{dz} =$$

$$Ag(1-\alpha) \rho_l \cos \theta - v_l^2 \rho_l(1-\alpha) \frac{dA}{dz} - AF_{l,wall} + AC_i |v_r| v_r - Av_i \Gamma$$

e) energy conservation for liquid phase:

$$A\rho_l(1-\alpha) \left(h_l + \frac{3v_l^2}{2} \right) \frac{dv_l}{dz} - Av_l \rho_l \left(h_l + \frac{v_l^2}{2} \right) \frac{d\alpha}{dz} + \quad (13)$$

$$Av_l \rho_l(1-\alpha) \frac{dh_l}{dz} = Agv_l(1-\alpha) \rho_l \cos \theta -$$

$$v_l \rho_l(1-\alpha) \left(h_l + \frac{v_l^2}{2} \right) \frac{dA}{dz} + AQ_{it} - A\Gamma \left(h_l + \frac{v_l^2}{2} \right)$$

The above set of equations can be transform into the matrix form:

$$B \frac{d\varepsilon}{dz} = C \quad (14)$$

and it further can be transformer to the following relation:

$$B^{-1} B \frac{\partial \varepsilon}{\partial z} = B^{-1} C \quad (15)$$

The injector may be treated as the momentum exchanger, therefore a key role in the model play the closure equations, especially for variable in momentum conservation equations. The following terms influence on momentum transfer between two phases in the model:

- $\Gamma(v_i - v_k)$ is the momentum transfer between phases at the interphase; here Γ is vapour mass condensed. In our case we assume that: $v_i = v_l$ and v_k is the velocity of phase (liquid or vapour).

- $AC_i |v_r| v_r$ describe the frictional stress at the interphase. Here: $v_r = v_g - v_l$.

- $A(1-S)C_{vm} \left(v_l \frac{\partial v_g}{\partial z} - v_g \frac{\partial v_l}{\partial z} \right)$ describe momentum transported with virtual mass due to movement of vapour bubbles. Term $(1-S)$ describe influence of flow structure on momentum transfer. The stratification parameter S enables the discussed set of equations is hyperbolic, Drew in [6].

- $Ap_i \frac{\partial \alpha}{\partial z}$ is the term where the so-called interphase pressure is used. In our case the interphase pressure has not a strict physical interpretation and is used in order to ensure the hyperbolic character of the discussed set of equations. For the separated two-phase flows the following relation is proposed by Tiselj in [11]

$$p_i = \alpha(1-\alpha) \Delta \rho g D_h \quad (16)$$

- The stratification parameter S defined by Carlson in [4] and Tiselj in [11] is used in the paper. The parameters C_{vm} and p_i depends on the stratification parameter. For separated flow $S=1$. The consequence of separated flow is diminishing of influence of C_{vm} on momentum transfer as well as increasing of the role of p_i . The following relation is proposed by Tiselj in [11]:

$$S = S_n X_i X_{\rho} X_{\alpha} X_{1-\alpha} \quad (17)$$

where the factors describe influence of various effects on the flow structure:

S_n - factor of Kelvin-Helmholtz instability;

X_i - factor of channel inclination;

X_{ρ} - factor of very high mass fluxes;

X_{α} - factor of very high or very small void fraction;

Condensation heat transfer plays a key role for the operation of the discussed injector. Based on the systematic experimental investigations Trela and Butrymowicz [12] proposed the following correlation describing condensation heat transfer in the injector:

$$Nu = 210.8943 \cdot 10^{-6} Re_v^{0.8-3.09561\Delta-0.134536X} Ja^{-1.86626+8.948750\Delta-0.067246X} Oh^{-0.362097-8.86765\Delta-0.211543X} \quad (18)$$

in the above equation is used dimensionless water feeding gap thickness:

$$\Delta = \frac{\delta}{D_{th}} \quad (19)$$

The further details of the model are presented in the report of Butrymowicz et al. [3].

RESULTS OF NUMERICAL CALCULATIONS

Two geometry configuration of the injector are presented in Fig. 4. There is a cylindrical throat of the mixing chamber in the case ‘B’ while in the case ‘A’ there is a sharp-edge throat. The case ‘A’ was investigated previously by the authors in paper [13].

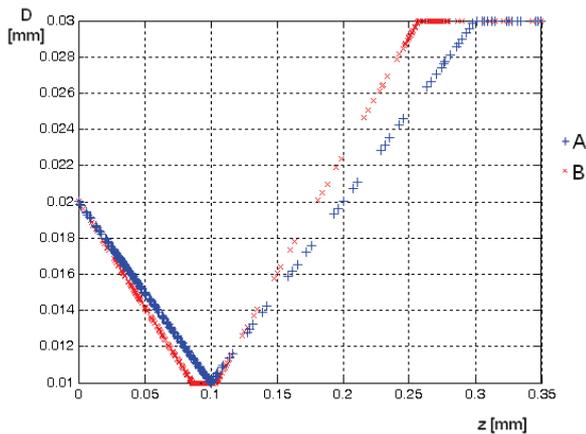


Fig. 4. Geometry of mixing chamber and diffuser with mesh grid of investigated injector. A - injector with sharp-edge throat; B - injector with cylindrical throat

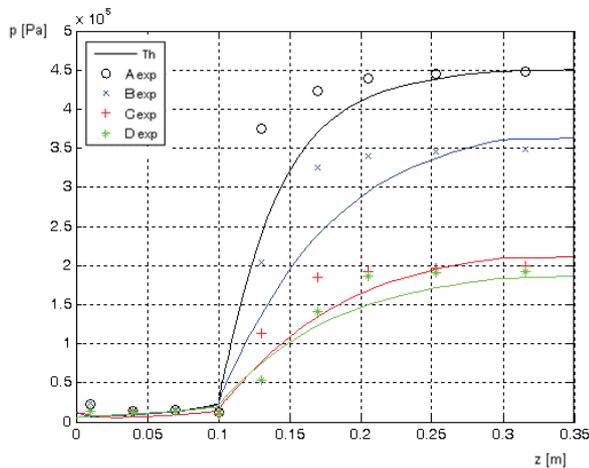


Fig. 5. Comparison of pressure profile calculated (lines) with experimental data for ejector with sharp-edge mixing chamber throat.

Table 1. Operating parameters for the injector calculations.

injector with sharp-edge throat		
run No.	discharge pressure [Pa]	volume rate of liquid [dm ³ /h]
A	$p_{out} = 448500$	$\dot{Q}_l = 4895.8$
B	$p_{out} = 349000$	$\dot{Q}_l = 4876.2$
C	$p_{out} = 199100$	$\dot{Q}_l = 4000.7$
D	$p_{out} = 191700$	$\dot{Q}_l = 3005.8$
injector with cylindrical throat		
run No.	discharge pressure [Pa]	volume rate of liquid [dm ³ /h]
A	$p_{out} = 492925$	$\dot{Q}_l = 4692$
B	$p_{out} = 454552$	$\dot{Q}_l = 4769.6$
C	$p_{out} = 388463$	$\dot{Q}_l = 4710.0$
D	$p_{out} = 279994$	$\dot{Q}_l = 4777.8$

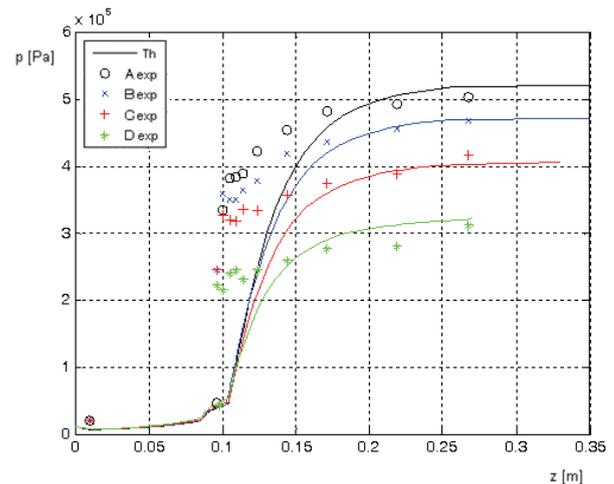


Fig. 6. Comparison of pressure profile calculated (lines) with experimental data for ejector with cylindrical throat of mixing chamber.

The numerical calculations have been carried out for the geometry of the injector investigated in [2]. The calculations of the operation of steam-water injector have been carried out for the operating parameters used in the experiments [2]. The operating parameters for various geometry are given in Table 1.

The calculation results are compared with experimental data in Fig. 4 and 5 for the case of sharp-edge throat and cylindrical throat of mixing chamber, respectively. A reasonably good agreement between calculation results and experiments was shown for the case ‘A’. In the case ‘B’ however, the calculated discharge pressure agrees very well with experiments, there is not very good prediction of the position of condensation shock wave (see Fig. 5). In the case ‘B’ experiments proved that shock-wave produce relatively higher pressure gradient in comparison with case ‘A’ which has been also obtained in presented calculations.

CONCLUSIONS

Two-fluid model have been applied to calculate pressure distribution in two-phase injector along with a set of closure equations used in the WAHA-3 code [11]. There is reasonably good agreement between experimental data and calculation results. However, there is a clear need to improve stratification model in order to better describe pressure rise within condensation shock wave, especially in the case of the injector with cylindrical throat of the mixing chamber.

NOMENCLATURE

A	- surface area cross-section, m^2
B	- Matrix, see Eq. (14)
c	- specific heat, $J/(kg \cdot K)$
C	- source-terms vector
C_i	- interfacial friction coefficient
C_{VM}	- virtual mass coefficient, kg/m^3
D	- diameter, m
e	- specific total energy, J/kg
F	- volume specific wall friction force, N/m^3
g	- gravity acceleration, kg/s^2
h	- specific enthalpy, J/kg
h_{fg}	- specific latent heat of vaporisation, J/kg
Ja	- Jacob number, $c_{p,l}(T_g - T_l)/h_{fg}$
Nu	- Nusselt number $\beta D/\lambda_l$
Oh	- Ohnesorge number $\mu_l/\sqrt{\sigma D \rho_l}$
p	- pressure, Pa
Re	- Reynolds number $\rho v D/\mu$
S	- stratification factor
v	- velocity, m/s
Q	- heat transfer rate per unit of volume [W/m^3]
X	- Martinelli parameter;
x	- quality
z	- spatial coordinate, m

Greek symbols

α	- void fraction;
β	heat transfer coefficient, $W/(m^2 \cdot K)$
δ	- liquid gap thickness, m
ε	- vector of state variables
λ	- thermal conductivity, $W/(m \cdot K)$
Γ	- vapor generation rate, $kg/(m^3 \cdot s)$
θ	- azimuth angle
μ	- dynamic viscosity, $kg/(m \cdot s)$
ρ	- density, kg/m^3
σ	- surface tension, N/m

Subscripts

g	- gas
i	- interface
l	- liquid
r	- relative quantity
s	- saturation
th	- throat.

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