Modeling wave processes at the outflowing of a water coolant with supercritical initial parameters

I S Vozhakov¹,², M V Alekseev¹, S I Lezhnin¹,², N A Pribaturin¹

¹ Institute of Thermophysics SB RAS, Ave. Lavrenteva 1, Novosibirsk 630090, Russia
² Novosibirsk State University, Pirogova St. 2, Novosibirsk 630090, Russia
E-mail: vozhakov@gmail.com

Abstract. Numerical simulation of the outflow of a coolant with supercritical initial parameters at a butt-break of high-pressure pipeline is carried out. The results of calculation of the outflow dynamics on a PV-diagram, as well as the pressure evolution are presented. It is shown that the flow rate weakly depends on temperature at its low values (up to 0.9 Tc). In the second region (from 0.9 Tc to Tc), the coolant boiling occurs inside the channel, which leads to a sharp drop in the flow rate with increasing temperature. And the third area (above Tc) is typical for the gas coolant outflow, in which the density strongly depends on pressure and temperature.

1. Introduction
The most important task in the design of power plants is the creation of units that are resistant to malfunctioning, including different types of emergencies. The use of water coolant under high pressure in power plants in the accidents associated with pipeline breaks causes outflowing of the superheated coolant in the atmosphere, followed by rapid (explosive) fluid boiling. At that a non-stationary compression wave [1, 2, 3] runs to external medium and damages other elements of the unit. The danger of this emergency scenario increases significantly in the modern power plants due to growing power density, where working pressure and temperature approach or exceed the critical values [4]. In this regard it is extremely important to be able to predict the scenarios of the process development in a sudden depressurization of such a working region. In addition, the study of shock-wave processes in the vicinity of the termodynamic critical point is interesting not only from the point of view of practical value, but raises questions of a fundamental character.

To date a large number of experimental data on adiabatic boiling flows has been obtained [5, 6]. However, the research area for the majority of substances lies in a relatively narrow range of values of pressure and temperature. However, it is interesting to observe the change in the flow rate through the channel at supercritical initial pressure and at a consistent temperature rise across the critical point. An extreme change of physical properties in the area of supercritical single-phase states may have a significant impact on the coolant outflow, boiling and generation of shock wave phenomena. In the present work, the outflow of water coolant with supercritical parameters is numerically studied at sudden depressurization of the pipeline.
2. The calculation method

The study considers the axisymmetric problem of the boiling coolant outflow from the pipe. The problem is described by the Euler equations in combination with the continuity equation and the energy equation for the two-phase homogeneous mixture:

\[
\frac{\partial}{\partial t} (\rho r) + \frac{\partial}{\partial z} (\rho ru) + \frac{\partial}{\partial r} (\rho rv) = 0 \tag{1}
\]

\[
\frac{\partial}{\partial t} (\rho ru) + \frac{\partial}{\partial z} (\rho u^2) + \frac{\partial}{\partial r} (\rho r uv) = -r \frac{\partial p}{\partial z} \tag{2}
\]

\[
\frac{\partial}{\partial t} (\rho rv) + \frac{\partial}{\partial z} (\rho rv) + \frac{\partial}{\partial r} (\rho r v^2) = -r \frac{\partial p}{\partial r} \tag{3}
\]

\[
\frac{\partial}{\partial t} (E_r) + \frac{\partial}{\partial z} (ur (E + p)) + \frac{\partial}{\partial r} (vr (E + p)) = 0 \tag{4}
\]

Here \(\rho\) – mixture density, \(u\) – axial velocity, \(v\) – radial velocity, \(p\) – pressure, \(E\) – energy.

To close the system of equations the equation of mixture state is used in the form that binds pressure, density and specific internal energy. The calculation of vapor and liquid properties is performed using the software package TTSE [7]. The solution to the original conservative system of equations is obtained by using the software package [8], applying the finite volume method coupled with the method of flow correction, FCT. The solution to the model equations by this method is equivalent to the application of some subgrid turbulence model [9]. The detailed description of the model is presented in works [10, 11, 12].

Simulation of liquid outflow from a vessel requires a simultaneous calculation of the flow in the vessel, in the pipeline and in the outside area. Conjugating the flow in the vessel and in the pipeline we apply a simplified “input area model” where an incompressible medium motion is described by one-dimensional Cauchy-Lagrange integral and which allows calculating pressure and velocity of fluid at a known pressure in the vessel. When simulating the external medium it is assumed that the vapor-liquid mixture outflows in the space, filled at atmospheric pressure by wet saturated vapor with density equal to that of air atmosphere at a temperature of 20 °C.

The process of non-equilibrium superheated boiling of the coolant is described using relaxation model, determining phase transition velocity on two parameters (temperature and pressure). It is assumed that the growth rate of the local mass vapor fraction \(X\) (equation of vapor generation) is proportional to its deviation from the equilibrium value \(X_s\), i.e.

\[
\frac{dX}{dt} = - \frac{X - X_s}{\theta} \tag{5}
\]

where \(\theta\) is the time of relaxation to equilibrium.

At that, it is assumed that parameters of the vapor phase (due to higher temperature diffusivity of vapor) correspond to equilibrium, and these of the liquid phase agree with the metastable state. The relaxation time \(\theta\) is determined in [13] from experimental data as a function of two parameters: the volumetric steam fraction \(\varepsilon\) and the relative differential pressure \(\psi = (P_s (T) - P) / P_s (T)\). On the basis of experimental data (pressures up to 1 MPa) processing the following is obtained:

\[
\theta = 6.51 \times 10^{-4} \varepsilon^{-0.257} \psi^{-0.224} \tag{6}
\]

For large pressures in the processing a different expression of the relative differential pressure is used: \(\phi = (P_s (T) - P) / (P_c (T) - P_s (T))\), where \(P_c\) is the pressure in critical
thermodynamical point. The corresponding formula for the relaxation time has the following form:

$$\theta = 3.84 \times 10^{-7} \varepsilon^{-0.54} \phi^{-1.76}. \quad (7)$$

3. The calculation results

In the vicinity of the critical point \( (P_c = 21.8 \text{ MPa}, T_c = 374^\circ \text{C} (647 \text{ K})) \) the derivative of the enthalpy by temperature (Fig. 1) increases dramatically since thermophysical parameters also experience changes. One can see that the dependence of specific enthalpy of water on temperature at different pressures has a jump when pressure approaches the critical point. Therefore, the proximity of initial parameters of the coolant to the critical point significantly affects the coolant outflow. Let us consider the model problem on the outflow of water coolant with supercritical initial parameters in the atmosphere.

![Figure 1. The dependence of specific enthalpy on temperature in the vicinity of the critical point (1 – \( P_0 = 23 \text{ MPa}, 2 – P_0 = 25 \text{ MPa}, 3 – P_0 = 30 \text{ MPa}, 4 – P_0 = 35 \text{ MPa} \).](image1)

![Figure 2. Comparison of theoretical isentropes and calculated curves of supercritical water outflow on PV-diagram (1 – boundary of two-phase area. 2 – theoretical isentropes, 3 – calculated curves).](image2)

Consider the \( PV \)-diagram with the calculated and theoretical curves for isentropic process (Fig. 2). The initial conditions of information output are chosen to take the calculated pressure at a distance of one caliber inwards from the pipe end on the pipe axis. The graph shows that in both cases the calculated curves with good accuracy coincide with the isentropic lines. Thus, in our case the liquid outflow is well described by the adiabatic approximation. At initial data \( P_0 = 23 \text{MPa} \) and \( T_0 = 370^\circ \text{C} \) the adiabatic line on \( PV \) diagram runs to the left from the critical point and crosses the line of boiling, i.e. enters the two-phase area with the void fraction equal to null. When the initial data take values \( P_0 = 23 \text{ MPa} \) and \( T_0 = 380^\circ \text{C} \), the adiabatic line passes to the right from the critical point and crosses the line of condensation, i.e. enters the two-phase region with the void fraction equal to one. Thus an insignificant difference in the initial data leads to a fundamentally different result of the coolant outflow.

Figure 3 shows calculated values of pressure depending on time. The process with initial temperature of \( T_0 = 380^\circ \text{C} \) is characterized by a sharp pressure drop after entering the two-phase area whereas a sharp pressure drop is not observed for the process with initial temperature of \( T_0 = 370^\circ \text{C} \). This is primarily due the fact that in the first case (curve 1) at the entrance to the two-phase area begins condensation, which considerably accelerates the pressure drop. In
the second case (curve 2) the coolant boiling occurs that compensates the pressure drop, caused by pipeline depressurization.

Figure 4 shows the dependence of the mass flow rate on temperature in the vicinity of the critical point at pressures above the critical. The flow rate weakly depends on temperature up to values $0.9 T_c$. Further, there is a rapid reduction in the flow rate, and at $T = T_{\text{min}}(P)$ the flow rate curves have a minimum. With increasing pressure, the value $T_{\text{min}}(P)$ is shifted towards higher temperature values. This behavior may be explained by different outflow modes. At low values of temperatures there is a hydraulic outflow at which boiling occurs only beyond the nozzle. With increasing temperature the boiling front is displaced to the nozzle area, which leads to a sharp drop in the flow rate. The results have not been obtained for the case when the temperature is much higher that the $T_c$, but it may be assumed that they should match the flow rate characteristics for gas. That is in this area it is necessary to consider a strong density dependence on pressure and temperature.

4. Conclusions
Simulating the outflow of the coolant with supercritical parameters requires the enhanced prediction accuracy, as small differences in initial data can lead to fundamentally different results. The results of simulating the outflow of coolant with supercritical initial parameters are qualitatively consistent with the results of [14], which experimentally studied the discharge characteristics of short cylindrical channels at the outflow of nitrogen with supercritical parameters into the atmosphere. The calculations have proved the presence of three areas in the description of discharge characteristics of the coolant with supercritical parameters at its outflow from the channel. So the first area corresponds to the hydraulic outflow and is characterized by a weak dependence on the coolant temperature. In the second region, the coolant boiling occurs inside the channel, which leads to a sharp drop in the flow rate with increasing temperature. The third area is typical for the gas coolant outflow, in which the density strongly depends on pressure and temperature [14].
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