Investigation on Flow Stability of Supercritical Water Cooled Systems

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1. Introduction

The supercritical pressure water cooled reactor (SCWR) offers the potential for high thermal efficiencies and considerable plant simplifications. One of the main features of supercritical water is the strong variation of their thermal-physical properties in the vicinity of the pseudo-critical line. This large variation of thermal-physical properties, especially the density variation, results in a serious concern of flow instability. Flow stability is a crucial issue in the design and operation of SCW cooled systems.

Theoretical investigations of the flow stability of supercritical fluids go back to the work of Zuber. In the cryogenic application, flow instability has also been intensively investigated for thermal-hydraulic systems cooled by supercritical fluids, e.g. supercritical helium. In the frame of the development of supercritical CANDU (CANDU-X) reactors, stability of supercritical water flow in a single channel under natural circulation conditions was investigated by Chatoorgoon. In that paper, supercritical flow stability was examined using a non-linear numerical code. In addition, a theoretical stability criterion is also established to verify the numerical prediction. This theoretical model is based on the assumption of zero gradient of mass flow by the heat power. However, the availability of this assumption is not proven, even for natural circulation loop.

In the present paper, the new computer code SASC (System Analyzer of Super-Critical fluid flows) has been developed. This code is applied to a simplified system cooled with supercritical water. The effect of various parameters on the flow behavior and flow stability has been studied.

2. SASC: A computer code for system analysis of SC flows

The SASC (System Analyzer of Super-Critical fluid flows) bases on one-dimensional conservation equations:

Continuity equation

$$\frac{\partial m}{\partial z} = - A \frac{\partial \rho}{\partial t}$$ (1)

Momentum conservation equation

$$\frac{1}{A} \frac{\partial m}{\partial t} + \frac{1}{A^2} \frac{\partial m^2}{\partial z} = - \frac{\partial P}{\partial z} - g \rho \cdot \cos(\theta) - \frac{f}{2D} \frac{m^2}{A^2 \rho}$$ (2)

Energy conservation equation

$$\frac{\partial \left( \frac{m \cdot h + \frac{m^3}{2A^2 \rho}}{\partial z} \right)}{\partial z} + A \frac{\partial \left( \frac{\rho \cdot e + \frac{m^2}{2A^2 \rho}}{\partial t} \right)}{\partial t} = \frac{\partial Q}{\partial z}$$ (3)

The conservation equations are integrated over the time step (t, t+Δt) and the space increment (z, z+Δz), we get from the continuity equation
\[ \rho_{j+1} = \rho_j - \frac{\Delta t}{A \Delta z} m_{j+1} - m_i \]  

(4)

and from the momentum conservation equation

\[ P_{j+1,i+1} = P_{j,i+1} + \frac{1}{A^2} \left( \frac{m^2}{\rho} \right)_{j,i+1} - \frac{1}{A^2} \left( \frac{m^2}{\rho} \right)_{j,i} - \frac{\Delta z}{A \cdot \Delta t} (m_{j+1} - m_j) - f \cdot \frac{\Delta z}{2 \cdot D} \cdot \frac{m^2}{A^2 \rho} \]  

(5)

and from the energy conservation equation

\[ A \Delta z (\rho \cdot e)_{j,i} - A \Delta z (\rho \cdot e)_{j,i+1} + \frac{\Delta z}{2A} \left( \frac{m^2}{\rho} \right)_{j,i+1} - \frac{\Delta z}{2A} \left( \frac{m^2}{\rho} \right)_{j,i} + (m \cdot h)_{j,i} \Delta t - (m \cdot h)_{j,i+1} \Delta t + \frac{\Delta t}{2A^2} \left( \frac{m^2}{\rho} \right)_{j,i+1} - \frac{\Delta z}{2A} \left( \frac{m^2}{\rho} \right)_{j,i} = \int_{t}^{t+\Delta t} Q \cdot dt \]  

(6)

The subscript i stands for the space coordinate z, i+1 for z+\Delta z, j for the time coordinate t and j+1 for t+\Delta t. Both values r and s have values ranging from 0 to 1.

The heat transfer quantity between the solid wall and the fluid Q is determined by solving the Fourier heat conduction equation for the solid material

\[ A_s \rho_s C_s \frac{\partial T_s}{\partial t} = A_s q_s + A_s \lambda_s \frac{\partial^2 T_s}{\partial z^2} - U \cdot \alpha \cdot (T_s - T) \]  

(7)

Solving the above equation yields

\[ \theta = \theta_0 \cdot e^{-b \tau} + \frac{c}{b} \left( 1 - e^{-b \tau} \right) \]  

(8)

with

\[ \theta = T_s - T, \quad \tau = t - t_j, \quad b = \frac{U \cdot \alpha}{A_s \rho_s C_s}, \quad c = \frac{q_s + \lambda_s}{\rho_s C_s} \]

The heat transfer quantity transferred from the solid material to the fluid is then evaluated from

\[ \int_{t}^{t+\Delta t} Q \cdot dt = F \cdot \frac{\alpha}{b} \theta_0 \cdot \frac{c}{b} \left( 1 - e^{-b \Delta t} \right) + F \cdot \frac{\alpha \cdot c}{b} \Delta t \]  

(9)

3 Results and discussion

The SASC code was applied to a simplified system configuration cooled by supercritical water, to assess the feasibility of the SASC code, to gather the first knowledge about the dynamic behaviour of SCW cooled systems, and to study the effect of various physical models on the system stability behaviour.

3.1 A simplified cooling system
The system considered is illustrated in figure 1, which is similar to that used in the study of Chatoorgoon4. It is a closed system with a pressure control vessel connected at the top of the loop. The pressure control vessel is large enough, so that the pressure fluctuation inside the vessel is negligibly small during the entire transient procedure. The loop consists of pipes of 78 mm inner diameter. The pipe line can be divided into four sections with a length of 6 m, 14 m, 6 m and 14 m, respectively. The four pipe sections are connected with bending connectors. The local pressure loss coefficient of each bending connectors is assumed to be 1.0. A pump is available in the loop. The heating zone is in the middle of the section 1 with a length of 3.6 m and with a uniform heat flux. One flow control valve is located before the inlet of the heating zone.

A fictive heat sink is located in the middle of the section 3 with a total length of 3.6 m. It is assumed that the fluid temperature at the exit of the heat sink is kept constant during the entire transient procedure and the removed heat is uniformly distributed over the entire length of the heat sink. Heat loss to the environment is neglected. Before the transient begins, certain flow rate is realized using the circulating pump. During the entire transient procedure, the pump head is assumed unchanged, independent of the flow rate. The pressure in the pressure control vessel is 25.0 MPa.

In the present analysis, several parameters, as summarized in table 1, are varied to study their effect on the transient behaviour. The initial mass flow rate is required to avoid numerical divergence of both flow rate and fluid temperature. The lowest value of the initial mass flow rate is 0.5 kg/s. This gives an initial velocity of about 0.16 m/s in the pipeline. The initial temperature, the same as the temperature at the exit of the heat sink, is changed from 300°C up to 375°C, which is slightly lower than the pseudo-critical temperature (384°C).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Reference</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial mass flow rate, kg/s</td>
<td>1.0</td>
<td>0.5 – 8.0</td>
</tr>
<tr>
<td>Initial temperature, °C</td>
<td>350</td>
<td>300 – 375</td>
</tr>
<tr>
<td>Hydraulic resistance of control valve ε, -</td>
<td>0.0</td>
<td>0.0 – 5.0</td>
</tr>
<tr>
<td>Pipe wall thickness, mm</td>
<td>1.0</td>
<td>1.0 – 5.0</td>
</tr>
</tbody>
</table>

The local pressure loss coefficient of the control valves is ranging from 0.0 up to 5.0. The pipeline is made of stainless steel with a uniform thickness profile. The pipe wall thickness acts as thermal inertia and will affect the transient behaviour. In the present study, the wall thickness is changed from the reference value (1.0 mm) up to 5.0 mm. Before the transient starts, no heat is added in the heating zone and removed in the heat sink zone. At the time point t=0, heat is fed to the heating zone with full power and the transient starts.

3.2 Results and discussions

Figure 2 shows the results at the reference condition. It is seen that after the heat power is added, the mass flow rate at the heating zone exit increases, whereas at the heating inlet decreases. Flow at the inlet goes in a reversal direction. This is due to the thermal expansion in the heating zone. After a short time period, the flow obtains a self-sustained oscillation with an oscillation period of about 11 s. This is also the time for the coolant travelling through the loop. The oscillation amplitude is high. The ratio of the maximum flow rate to the minimum flow rate is 3 at the heating zone exit and 8 at the heating zone inlet. The high flow rate (compared to the initial value) is resulted by the strong buoyancy force. The temperature at the heating zone
exit exhibits also a self sustained oscillation with the same period. The oscillation amplitude is about 30°C, ranging from 377°C to 407°C.

Figure 2: Results at the reference condition.

Figure 3 shows the effect of the initial mass flow rate, which varies from 1.0 kg/s to 4.0 kg/s. It is found that a higher initial mass flow rate leads to a much smaller oscillation amplitude. At the initial mass flow rate of 4 kg/s, the oscillation amplitude tends to decrease slowly with the time. It has to be pointed out that at an initial mass flow rate of 8 kg/s, no self-sustained oscillation is observed. This is because of the reduced buoyancy effect.

Figure 4 shows the effect of the initial temperature. At low inlet temperatures, e.g. 300°C, no self-sustained oscillation is observed. The oscillation damps down after a few periods and converges to a steady state solution. The mass flow rate at the steady state condition is about 6 kg/s. This indicates the strong buoyancy force. The temperature is about 10°C lower than the pseudo-critical value. By increasing the inlet temperature from 300°C to 330°C, a strong flow oscillation occurs. The ratio of the maximum to the minimum mass flow rate is as high as 4. The temperature at the heating zone exit oscillates around the pseudo-critical value. By a further increase in the inlet temperature to 350°C, the oscillation amplitude decreases. The hot temperature oscillates over the pseudo-critical value. The oscillation disappears completely, if the inlet temperature is increased to 375°C. The coolant temperature at the steady state is about 15°C higher than the pseudo-critical value. The mass flow rate at the steady state is about 4 kg/s, 50% lower than that in the case with an inlet temperature of 300°C. This is due to the combined effects of buoyancy force and hydraulic resistance in the loop, which is sensitive to the distribution of the coolant density in the loop.
The effect of the hydraulic resistance at the heating zone inlet is indicated in figure 5. A higher hydraulic resistance at the inlet of the heating zone stabilizes the flow. The self-sustained oscillation disappears by increasing the hydraulic resistance coefficient from zero to 5. However, it has to be kept in mind that a higher hydraulic resistance in the loop would reduce the natural convection capability.

Figure 6 presents the effect of the wall thickness, i.e. 1 mm and 3 mm. In case with a thin pipe, a strong flow oscillation occurs, whereas flow in a thicker pipe doesn’t undergo self-sustained oscillation. A thicker wall gives a strong thermal inertia, which obviously delays the heat transfer between the wall and the coolant, and subsequently, damps the flow oscillation.
4 Conclusions

The strong variation of the thermal-physical properties of water in the vicinity of the pseudo-critical line motivates the investigation on the dynamic behavior and flow stability of supercritical water cooled systems. In the present work, the computer code SASC (System Analyzer for Supercritical fluid flows) was developed and applied to a simplified cooling system with the objectives to assess the feasibility of the SASC code, to gather the first knowledge of the dynamic behaviour of SCW cooled systems, and to study the effect of various physical models on the system stability behaviour.

For the cooling system considered, self-sustainable oscillation is observed under various conditions. In the case with self-sustainable oscillation, the temperature at the exit of the heating zone oscillates around the pseudo-critical value. Steady state conditions are obtained with a coolant temperature at the exit of the heating zone below or far beyond the pseudo-critical value. A cooling system with a higher buoyancy force tends more easily to instability. A higher hydraulic resistance at the inlet of the heating zone would stabilize the flow. A larger thermal inertia of the wall acts as a stabilization of the flow.

In the next step, the SASC code will be modified to include the performance of control systems, e.g. pressure control, and applied to design analysis of thermal-hydraulic test loops. This code will also be extended to analyze flows in parallel channels and flows in SCW reactor cores. In addition, efforts will be made to derive theoretical models for predicting the transition between stable and unstable flows.

5 References