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Thermal-Hydraulic Simulation of Supercritical-Water-Cooled Reactors

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1. Introduction

At supercritical pressures the distinction between the liquid and gas phases disappears, and any fluid stays in a single continuous phase: no evaporation or condensation is observed. At supercritical state the thermo-physical properties of the fluid, such as density and viscosity, change smoothly from those of a liquid-like fluid to those of a gas-like fluid as the fluid is heated. Because of the single-phase nature, a one-phase model would be ideal for thermal-hydraulic simulation above the critical pressure. However, in the nuclear power plant applications the one-phase model is not sufficient, because in transient and accident scenarios, the pressure may drop below the critical pressure, turning the coolant abruptly from a one-phase fluid into a two-phase mixture. Therefore the thermal-hydraulic model has to be able to reliably simulate not only supercritical pressure flows but also flows in the two-phase conditions, and thus the six-equation model has to be used.

When the six-equation model is applied to supercritical-pressure calculation, the questions how the model behaves near and above the critical pressure, and how the phase transition through the supercritical-pressure region is handled, are inevitably encountered. Above the critical pressure the latent heat of evaporation disappears and the whole concept of phase change is no longer meaningful. The set of constitutive equations needed in the six-equation solution including friction and heat transfer correlations, has been developed separately for both phases. The capability of constitutive equations, and the way how they are used above the supercritical pressure point, have to be carefully examined.

In this article, the thermal hydraulic simulation model, which has been implemented in the system code APROS, is presented and discussed. Test cases, which prove the validity of the model, are depicted. Finally, the HPLWR concept is used as a pilot simulation case and selected simulation results are presented.

2. Modeling of supercritical fluid thermal hydraulics

One possibility to maintain separate liquid and gas phases in the supercritical flow model is to use a small evaporation heat, and then apply the concept of the pseudo-critical line. The pseudo-critical line is an extension of the saturation curve to the supercritical pressure region: it starts from the point where the saturation curve ends (the critical point), and it can

be thought to approximately divide the supercritical pressure region to sub-regions of pseudo-liquid and pseudo-gas. The thermo-physical properties of water and steam undergo rapid changes near the pseudo-critical line and therefore the quality and accuracy of the steam tables is essential in calculation of flows under supercritical conditions. One difficult problem is related to the heat transfer at supercritical pressures; if the ratio of the heat flux to mass flux exceeds certain value and flow is directed upwards, the heat transfer rate may suddenly be reduced, and remarkable heat transfer deterioration may occur. The same phenomena may occur due to flow acceleration. The present heat transfer correlations are not able to predict properly this phenomenon. However, in conditions where this heat transfer impairment does not occur, heat transfer rates can be predicted with a reasonable accuracy using the currently-available correlations. Another issue that has to be taken into account in thermal hydraulic simulations of SCW reactors is the possible appearance of flow instabilities. Similarly to the boiling water reactors, instabilities in the core of SCWR may appear when the ratio of the heat flux to mass flux exceeds a certain value.

3. Solution principles of the six-equation model

At present, the system-scale safety analyses of nuclear power plants are generally calculated using the six-equation flow model. The safety analyses conducted for a particular nuclear power plant include mainly different loss-of-coolant scenarios, where the pressure in the primary circuit decreases at a rate depending on the size of the break. This means that also in the case of supercritical-water-cooled reactors, boiling may occur during accident conditions, and therefore also the simulation tools used for the safety analyses of the SCWR's have to be able to calculate similar two-phase phenomena as in the present nuclear reactors. A practical way to develop a supercritical pressure safety code, is to take a present code and modify it to cope with the physical features at supercritical pressures.

The six-equation model of APROS used for the two-phase thermal hydraulics is based on the one-dimensional partial differential equation system which expresses the conservation principles of mass, momentum and energy (Siikonen 1987). When these equations are written separately for both the liquid and the gas phase, altogether six partial differential equations are obtained. The equations are of the form

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \frac{\partial(\alpha_k \rho_k u_k)}{\partial z} = \Gamma_k \,, \tag{1}$$

$$\frac{\partial(\alpha_k \rho_k u_k)}{\partial t} + \frac{\partial(\alpha_k \rho_k u_k^2)}{\partial z} = \Gamma_k \, u_{ik} + \alpha_k \rho_k \vec{g} + F_{wk} + F_{ik} \,, \tag{2}$$

$$\frac{\partial(\alpha_k \rho_k h_k)}{\partial t} + \frac{\partial(\alpha_k \rho_k u_k h_k)}{\partial z} = \alpha_k \frac{\partial p}{\partial t} + \Gamma_k \, h_{ik} + q_{ik} + F_{wk} u_k + F_{ik} u_{ik} \,. \tag{3}$$

In the equations, the subscript k is either l (= liquid) or g (= gas). The subscript i refers to interface and the subscript w to the wall. The term Γ is the mass change rate between phases (evaporation as positive), and the terms F and q denote friction force and heat transfer rate. For practical reasons, the energy equation (3) is written in terms of the total enthalpy, which equals to conventional "static" enthalpy plus all the kinetic energy: $h = h_{stat} + 1/2\mathrm{u}^2$.

The equations are discretized with respect to space and time and the non-linear terms are linearized in order to allow the use of an iterative solution procedure (Hänninen & Ylijoki). For the spatial discretization a staggered scheme has been applied, meaning that mass and energy balances are solved in one calculation mesh, and the momentum balances in another. The state variables, such as pressure, steam volume fraction, as well as enthalpy and density of both phases, are calculated in the centre of the mass mesh cells and the flow related variables, such as gas and liquid velocities, are calculated at the border between two mass mesh cells. In solving the enthalpies, the first order upwind scheme has been utilized normally. In the mesh cell, the quantities are averaged over the whole mesh, i.e. no distribution is used.

In the case of the APROS code, the main idea in the solution algorithm is that the liquid and gas velocities in the mass equation are substituted by the velocities from the linearized momentum equation. In the momentum equation the linearization has been made only for the local momentum flow. For the upwind momentum flows the values of the previous iteration is used. In addition the phase densities are linearized with respect to pressure. The density is linearized as

$$\rho_k^n = \rho_k + \frac{\partial \rho_k}{\partial p}\left(p^n - p\right), \tag{4}$$

where the superscript n refers to the value at the new time step. When this linearization is made together with eliminating phase velocities with the aid of the linearized momentum equation, a linear equation group, where the pressures are the only unknown variables is formed. Solution of this equation system requires that the derivatives of density are always positive, and also the phase densities obtained from the steam table are increasing with increasing pressure.

In the one-dimensional formulation, phenomena that depend on gradients transverse to the main flow direction, like friction and heat transfer between the gas and liquid phases, and between the wall and the fluid phases, have to be described through constitutive equations, which are normally expressed as empirical correlations. These additional equations are needed to close the system formed by six discretized partial differential equations.

4. Application of the six-equation model to supercritical-pressure flow

When the six-equation model is applied to supercritical-pressure calculation, the problems how the model behaves near and above the critical pressure, and how the phase transition needed in two-phase model is handled when the pressure exceeds the supercritical line, are inevitably encountered. Above the critical pressure the heat of evaporation disappears and the whole concept of phase change is no longer meaningful. The set of constitutive equations needed in the six-equation solution includes friction and heat transfer correlations that are developed separately for both phases. Also, many of the material properties exhibit sharp changes near the pseudo-critical line, and therefore correlations developed for subcritical pressures cannot give sensible values, and thus special correlations developed for supercritical pressure region have to be used instead. Then, how the transition from the subcritical to supercritical takes place, has to be taken into account in developing the correlation structure for friction and heat transfer. The capability of constitutive equations and the way how they are used has to be carefully examined (Hänninen & Kurki, 2008).

In system codes, the thermo-physical properties of the fluids are often given as tabulated values as a function of pressure and enthalpy. Especially for values near the critical point, a very dense network of the tabulated pressure and enthalpy points is needed in order to ensure the accuracy of the used property values. The heat capacities of the liquid and steam approach simultaneously infinity as the latent heat of evaporation approaches zero. In addition, the density and viscosity experience the sharp changes near the critical line (see Figure 1).

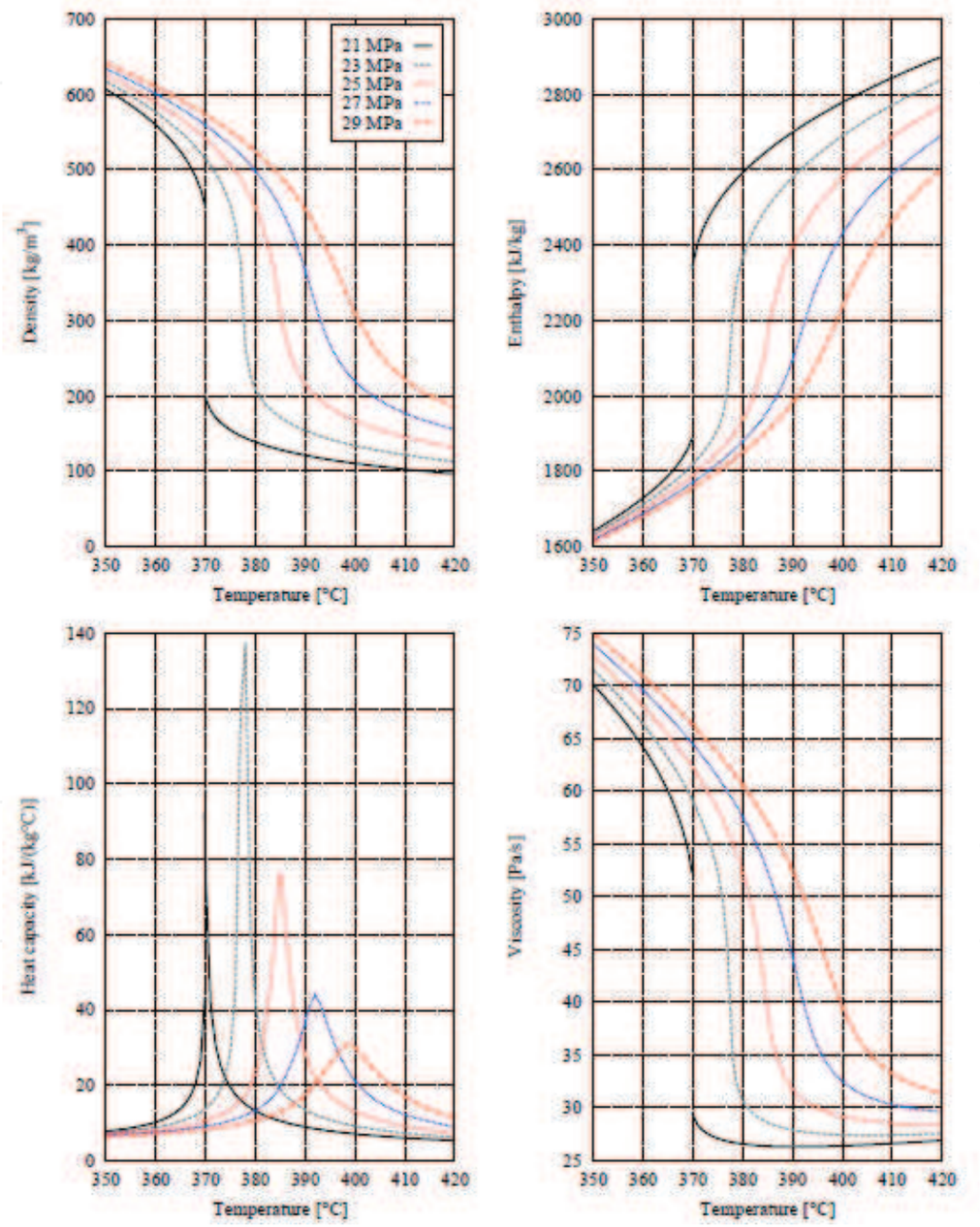


Fig. 1. Thermo-physical properties of water near the pseudo-critical line at various pressures

5. Treatment of phase change

In order to keep the solution structure close to the original two-phase flow model at the supercritical pressure region, the mass transfer rate between the pseudo-liquid and the pseudo-gas is calculated and taken into account in the mass and energy equations of both phases. At subcritical pressures the mass transfer is calculated from the equation

$$\Gamma = -\frac{q_{\mathrm{i1}} + q_{\mathrm{ig},} - q_{\mathrm{wi}}}{h_{\mathrm{g,\,sat}} - h_{\mathrm{l,\,sat}}} \tag{5}$$

In Equation (5) the heat fluxes from liquid to interface and from gas to interface q_{il} and q_{ig} are calculated using the interface heat transfer coefficients based on experimental correlations. The term q_{wi} is the heat flux from wall directly to the interface used for evaporation and condensation. Because at supercritical pressures the mass transfer rate doesn't have any physical meaning it was found to be more practical instead of using the heat fluxes just to force the state of the fluid either to pseudo-liquid or to pseudo-gas. This was done by introducing model for forced mass transfer. In this model the heat flux from wall to interface q_{wi} was omitted. The forced mass transfer is then calculated as

$$\Gamma_{\mathrm{F}} = \begin{cases} \dfrac{\left(1-\alpha^{t-\Delta t}\right)\rho_{\mathrm{l}}^{t-\Delta t}}{\Delta t} + \dfrac{\dot{m}_{in,\mathrm{l}}}{\Delta t}, & \text{if } h_{\mathrm{b}} > h_{\mathrm{sat,l}} \\ \dfrac{\alpha^{t-\Delta t}\rho_{\mathrm{g}}^{t-\Delta t}}{\Delta t} - \dfrac{\dot{m}_{\mathrm{in,g}}}{\Delta t}, & \text{if } h_{\mathrm{b}} < h_{\mathrm{sat,g}} \\ 0, & \text{if } \quad h < h_{\mathrm{b}} < h_{\mathrm{sat,g}} \end{cases} \tag{6}$$

For the treatment of the pseudo evaporation/condensation the concept of the pseudo-latent-heat is needed to separate the saturation enthalpies of liquid and gas. By using the pseudo-latent heat the pseudo-saturation enthalpies of liquid and gas can be expressed as

$$h_{\mathrm{sat,l}} = h_{\mathrm{pc}} - \frac{h_{\mathrm{lg}}}{2} \tag{7}$$

$$h_{\mathrm{sat,g}} = h_{\mathrm{pc}} + \frac{h_{\mathrm{lg}}}{2} \tag{8}$$

In Equations (7) and (8) the pseudo latent heat h_{lg} is chosen to be small in order to have fast enough transition from pseudo liquid to pseudo gas or vice versa. The use of very small value for pseudo latent heat (< 100 J/kg) may require small time steps to avoid numerical problems. However, it is also important that the transition does not happen too slowly, because a state with the presence of two separate phases with different temperatures at the same time is not physical.

The calculated mass transfer rate is taken into account in mass, momentum and energy equations of both phases. The pseudo saturation enthalpies are used when the interfacial heat transfer rates are calculated to fulfill the energy balances of the two fluid phases.

The presented model has been widely tested and it works well even for very fast transients (Kurki & Hänninen, 2010, Kurki 2010).

6. Wall heat transfer

Above the critical pressure the boiling and condensation phenomena cease to exist and only one-phase convection occurs. Due to the pseudo two-phase conditions convection has to be calculated for both the liquid and the gas phase. In the model the heat transfer coefficient is calculated by weighing the pseudo liquid and gas phase coefficients with the gas volumetric fraction, i.e. the supercritical coefficient is calculated as

$$\mathrm{Nu_b} = \alpha\,\mathrm{Nu_{ps,g}} + (1-\alpha)\,\mathrm{Nu_{ps,l}} \tag{9}$$

The subscript b refers to bulk fluid, and the subscripts ps,g and ps,l to pseudo-gas and pseudo-liquid. In the model most of time void fraction *a* is either 1 or 0, i.e. the case where liquid and gas are at different state is temporary. The transition speed from pseudo liquid to pseudo gas depends on the size of the pseudo evaporation heat and on the model to calculate the mass and energy transfer between phases.

Above the critical pressure point the forced-convection heat transfer from wall to both pseudo liquid and pseudo gas is calculated with the correlation of Jackson and Hall (Jackson 2008). The exponent *n* depends on the ratios of bulk-, wall- and pseudo-critical temperatures. The correlation gives good values for the supercritical pressure heat transfer, but it does not predict the deterioration of heat transfer.

$$\mathrm{Nu}_b = 0.0183\mathrm{Re}_b^{0.82}\mathrm{Pr}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{c_p}}{c_{p,b}}\right)^{n} \tag{10}$$

$$n = \begin{cases} 0.4, & \text{if } T_b < T_w < T_{\mathrm{pc}} \quad \text{or} \quad 1.2\mathrm{T_{pc}} < T_b < T_w \\ 0.4 + 0.2\left(\dfrac{T_w}{T_{\mathrm{pc}}} - 1\right), & \text{if } T_b < T_{\mathrm{pc}} < T_w \\ 0.4 + 0.2\left(\dfrac{T_w}{T_{\mathrm{pc}}} - 1\right)\left(1 - 5\left(\dfrac{T_b}{T_{\mathrm{pc}}} - 1\right)\right), & \text{if } T_{\mathrm{pc}} < T_b < 1.2\mathrm{T_{pc}} \quad \text{and} \quad T_b < T_w \end{cases}$$

The heat capacity $\overline{c}_p$ is calculated as an average of values in bulk flow and at wall conditions. In the six-equation model of APROS, also three other forced-convection heat transfer correlations are available as an option. The commonly used subcritical-pressure correlation of Dittus and Boelter gives reasonable values in some situations but in general it exaggerates the heat transfer near the critical point. This is due to extreme high heat capacity value near the critical pressure point (see Figure 1).

Two other forced-convection correlations implemented in APROS are those of Bishop and Watts and Chou (Watts and Chou, 1982). Again, the correlations give generally sensible prediction of the heat transfer coefficient, but only in the absence of the heat transfer deterioration phenomena caused by flow acceleration and buoyancy.

The Watts and Chou correlation uses a buoyancy parameter that tries to take into account the density difference between the fluid at wall temperature and the fluid at the bulk temperature.

For vertical upward flow, the correlation takes the form

$$\mathrm{Nu}_\mathrm{b} = \begin{cases} \mathrm{Nu}_\mathrm{var}\left(1-3000\chi\right)^{0.295}, & \text{if } 10^{-5} \le \chi \le 10^{-4} \\ \mathrm{Nu}_\mathrm{var}\left(7000\chi\right)^{0.295}, & \text{if } 10^{-4} < \chi \end{cases} \tag{11}$$

For vertical downward flow the correlation gives the Nusselt number as

$$\mathrm{Nu}_\mathrm{b} = \mathrm{Nu}_\mathrm{var}\left(1+30000\chi\right)^{0.295},$$

meaning that heat transfer is enhanced when the influence of buoyancy is increased. The term Nu_var takes into account "normal" convection and material property terms

$$\mathrm{Nu}_\mathrm{var} = 0.021\mathrm{Re}_\mathrm{b}^{0.8}\,\overline{\mathrm{Pr}}^{0.55}\left(\rho_\mathrm{w}/\rho_\mathrm{b}\right)^{0.35},$$

and the buoyancy parameter is defined as

$$\chi = \overline{\mathrm{Gr}}_\mathrm{b}/\left(\mathrm{Re}_\mathrm{b}^{2.7}\,\overline{\mathrm{Pr}}_\mathrm{b}^{0.5}\right).$$

It can be seen that with the buoyancy parameter from 10^{-5} to 10^{-4} the Nusselt number is decreasing with increasing values of the buoyancy parameter (about 10 %) and above 10^{-4} Nusselt number is increasing.
This correlation takes into account buoyancy-influenced heat transfer but it does not take into account the acceleration-influenced heat transfer impairment.

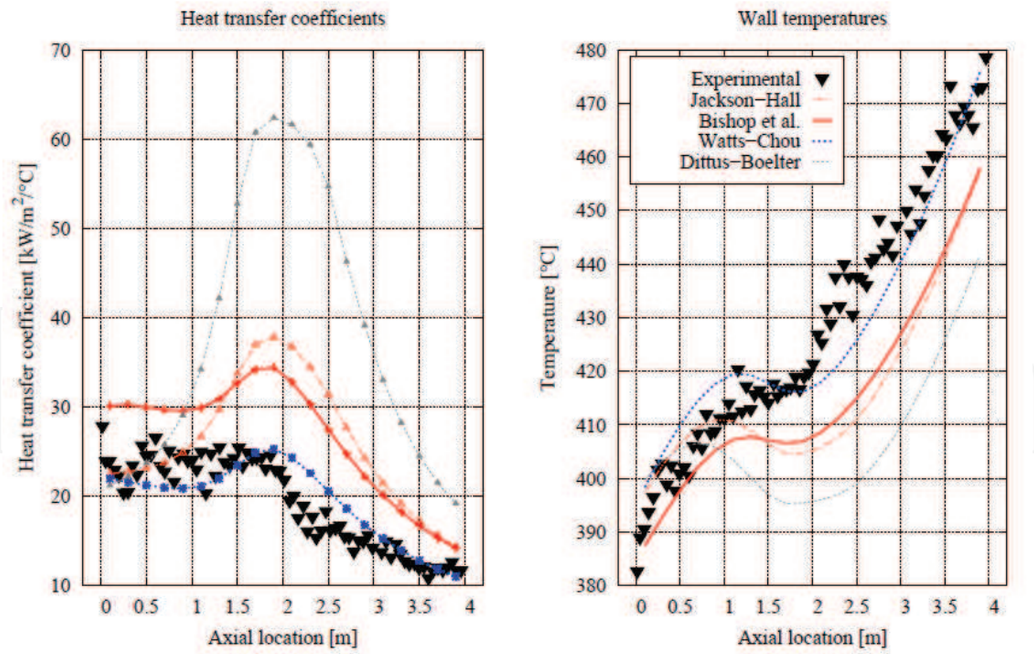


Fig. 2. Heated vertical pipe (IAEA benchmark 1). Effect of different heat transfer correlations, calculated with APROS (Kurki 2010). Experimental data are from (Kirillov et. al., 2005)

APROS includes the four heat transfer correlations which can be used at supercritical pressure flows - Dittus-Boelter, Bishop, Jackson-Hall and Watts-Chou. These correlations

were used for simulating a test case (Kirillov et. al., 2005), in which the steady-state heat transfer behaviour in a heated vertical pipe was analysed for both upwards and downwards flows (see Figure 2). The length of pipe was 4 m, the inner diameter was 1 cm, pressure at outlet was 24.05 MPa, inlet temperature was 352 ^{o}C and mass flux was 0.1178 kg/m^{2}s. In case of upwards flow the weak impairment of heat transfer occurs. It can be seen that the Watts-Chou correlation is able to predict this quite well, while the Dittus-Boelter correlation gives much too high values. The reason for too high values is that the heat capacity used in Prandtl number increase strongly near the pseudo saturation state of 24 MPa. For downward flow all of the correlations give sensible values – again Watts-Chou giving the closest values. It should be kept in mind that this is only one example. It has been found that any of available heat transfer correlations cannot predict the heat transfer impairments at all conditions.

7. Wall friction

Estimation of two-phase flow wall friction in system codes is generally based on single-phase friction factors, which are then corrected for the presence of two separate phases using special two-phase multipliers. The wall friction factor for single phase flow is often calculated using the Colebrook equation, which takes into account also the roughness of the wall

$$\frac{1}{\sqrt{f_{\mathrm{col}}}} = 1.74 - 2\log\left[\frac{1}{\sqrt{f_{\mathrm{col}}}}\frac{18.7}{\mathrm{Re}} + 2\frac{\varepsilon}{D_H}\right], \tag{12}$$

where ε is the relative roughness of the flow channel wall.

Because at supercritical pressures the variations of the thermophysical properties as a function of temperature may be very rapid, the properties near a heated wall – where the skin friction takes place – may differ considerably from the bulk properties. The friction factors can be corrected to take this into account by multiplying the factor by the ratio of a property calculated at the wall temperature to property calculated at the bulk fluid temperature. One of the friction correlations intended for supercritical pressure is the correlation of Kirillov

$$f_{\mathrm{kir}} = \left(1.82\log_{10}\mathrm{Re}_{\mathrm{b}} - 1.64\right)^{-2}\left(\frac{\rho_{\mathrm{w}}}{\rho_{\mathrm{b}}}\right)^{0.4} \tag{13}$$

This correlation has been formed by multiplying the friction factor correlation of Filonenko (the first term) by a correction term based on the ratio of densities calculated at wall and bulk temperatures respectively. However, this correlation is valid only for flows in smooth pipes.

Since no wall friction correlation for supercritical-pressure flows in rough pipes is available in the open literature, a pragmatic approach was taken in APROS to make it possible to estimate the wall friction in such a situation: the friction factor obtained from the Colebrook equation is simply multiplied by the same correction term that was used by Kirillov to extend the applicability of the Filonenko correlation, thus the friction factor may be calculated as

$$f = f_{\mathrm{col}}\left(\frac{\rho_{\mathrm{w}}}{\rho_{\mathrm{b}}}\right)^{0.4} \tag{14}$$

It is important to notice that this correlation is not based on any real data, and as such it must not be used for any real-life purposes before it has been carefully validated against experimental results. Thus, this form of the correlation serves only for preliminary estimation of the effect of friction and is mainly intended for reference purposes (Kurki 2010).

8. Flow instabilities in heated channels

In simulating flows and heat transfer at the supercritical pressure region the possibility of appearance of flow instabilities should be taken into account. Due to the rapid changes of density and viscosity with changing temperature near the pseudocritical line, different types of flow instabilities may occur. These instabilities are analogous to those related to boiling in vertical pipes, and may be of the Ledinegg or the density-wave-oscillation (DWO) type. Useful dimensionless parameters for defining the condition for stable or instable flows in heated pipes are the sub-pseudo-critical and trans-pseudo-critical numbers proposed in (Ambrosini & Sharabi 2006 and 2008).

The sub-pseudo-critical number describes the sub-cooling at the inlet of the heated pipe section, and is calculated as

$$\mathrm{N}_{\mathrm{spc}} = \frac{\beta_{\mathrm{pc}}}{c_{p,\mathrm{pc}}}\left(h_{\mathrm{pc}} - h_{\mathrm{in}}\right), \tag{15}$$

while the trans-pseudo-critical number represents the proportion of heating power to mass flux, and is defined as

$$\mathrm{N}_{\mathrm{tpc}} = \frac{P}{\dot{m}_{\mathrm{in}}}\frac{\beta_{\mathrm{pc}}}{c_{p,\mathrm{pc}}} \ . \tag{16}$$

With these two parameters the threshold for instabilities and the instable and stable flow areas can be estimated.

In the reference (Ambrosini & Sharabi, 2008) the stability boundaries of one particular geometry as function of N_{spc} and N_{tpc} calculated with RELAP5 are shown. The calculated values in the charts have been obtained by simulating the case where the flow under supercritical pressure flows through a vertical uniformly heated circular pipe. At the inlet, the constant singular pressure loss coefficient of K_{in} =10.5 and at the outlet the coefficients of K_{out} = 0.0 and 3.0 were applied. The pressure at inlet and at outlet is kept constant, but the heating rate is gradually increased, which results in a slowly increasing trans-pseudo-critical number. The calculation was repeated with different sub-pseudo-critical numbers corresponding to different inlet conditions. With a certain trans-pseudo-critical number, the flow changes from stable to oscillating or experiences the flow excursion. In the charts the instability threshold is presented when the amplifying parameter Zr has the value zero. The instability values above the position, where the second derivative changes strongly, represent the Ledinegg instabilities (N_{spc} about 3). The values below N_{spc} about 3 stand for

density instabilities. As an example, two calculation results obtained with APROS have been shown in Figures 3 and 4. In Figure 3 the typical behavior of a DWO-type instability is shown. The result representing the Ledinegg instability is presented in Figure 4.

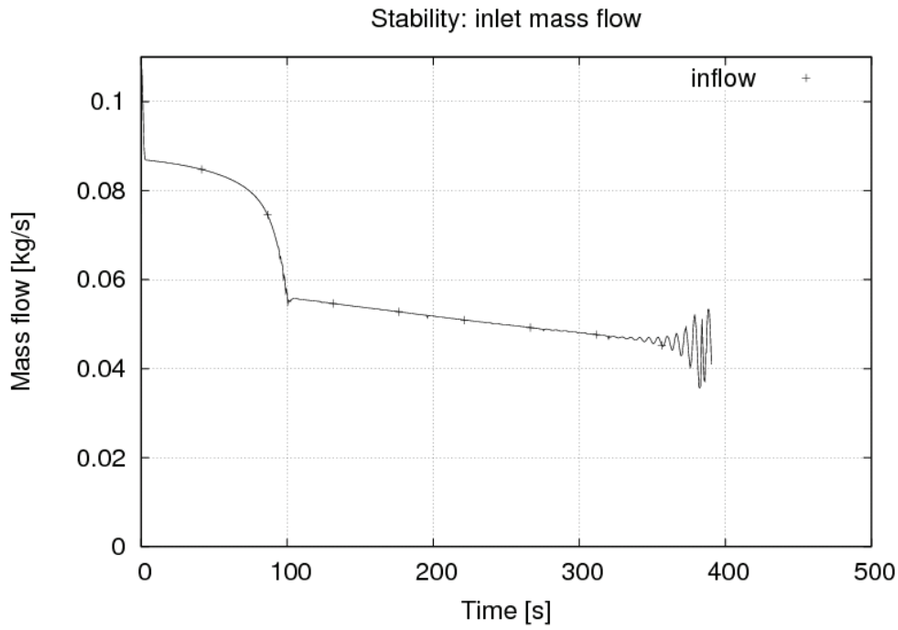


Fig. 3. Example of oscillating type (density) instability (IAEA benchmark 2, N_{spc} = 2.0, K_{in} = 20, K_{out} = 20), Calculated with APROS

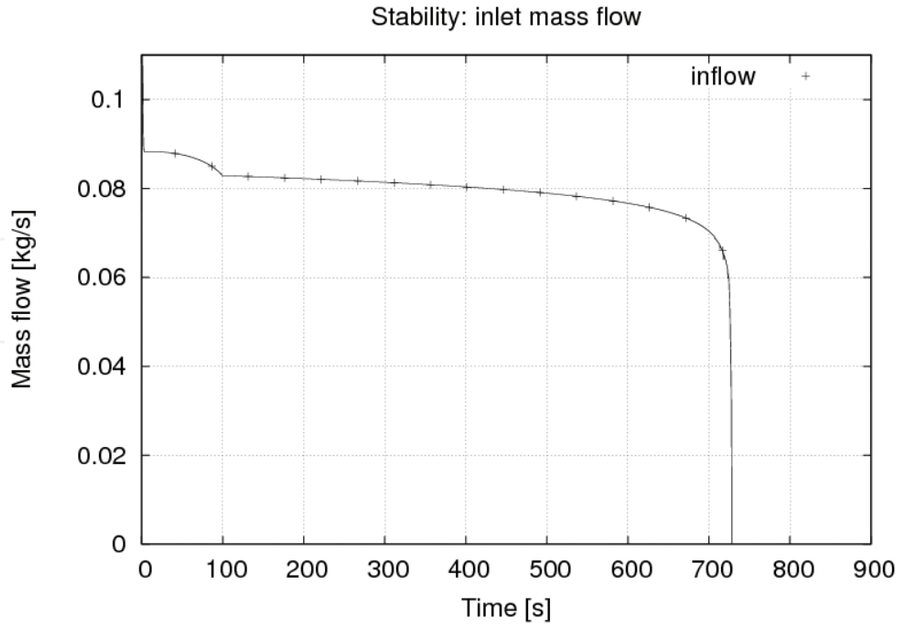


Fig. 4. Example of excursion type (Ledinegg) instability (N_{spc} = 3.0, K_{in} = 20, K_{out} = 20), Calculated with APROS

9. Simulation application – European concept of supercritical reactor (HPLWR)

In an European collaboration project, the concept of a new reactor working under the supercritical pressure has been developed (Schulenberg & al. 2008). This concept, called High Performance Light Water Reactor (HPLWR), has a three-pass core (Fischer & al, 2009), which was introduced to the design for preventing the formation of hot spots in the reactor core. The coolant flows through the core three times in the radially separated evaporator, super-heater 1 and super-heater 2 sections. Half of the feed water coming into the reactor pressure vessel is directed upwards to the upper plenum in order to provide neutron moderation for the reactor core and the other half flows to the downcomer, from where it continues to the core coolant channels. Also for the moderator, a three-stage flow scheme is applied.

For some preliminary accident analyses of the HPLWR safety concept, the APROS system code was used (Kurki & Hänninen, 2010). The intention of calculation was on the other hand make a typical large break LOCA analysis and also to verify the feasibility of the tentative protection system. The accident which was analysed was a guillotine break of one of the four steam lines. The accident was initiated by a 2 x 100 % break between the pressure vessel outlet and the main steam line isolation valve. Decreasing pressure at the pressure vessel outlet (p_{out} < 225 bar) initiates the reactor scram sequence and closure of the main steam line isolation valves (MSIV). The time taken for fully closing the isolation valves is assumed to be 3.5 seconds. After the MSIV has been shut, the effective break size is 1 x 100 %.

The calculation results (see Figure 5) suggested that with the assumed protection strategy and with the used safety injection capacity the reactor core of the HPLWR can be kept sufficiently cooled-down in the case of a large break LOCA caused by rupture of one of the four main steam lines, using the designed safety systems.

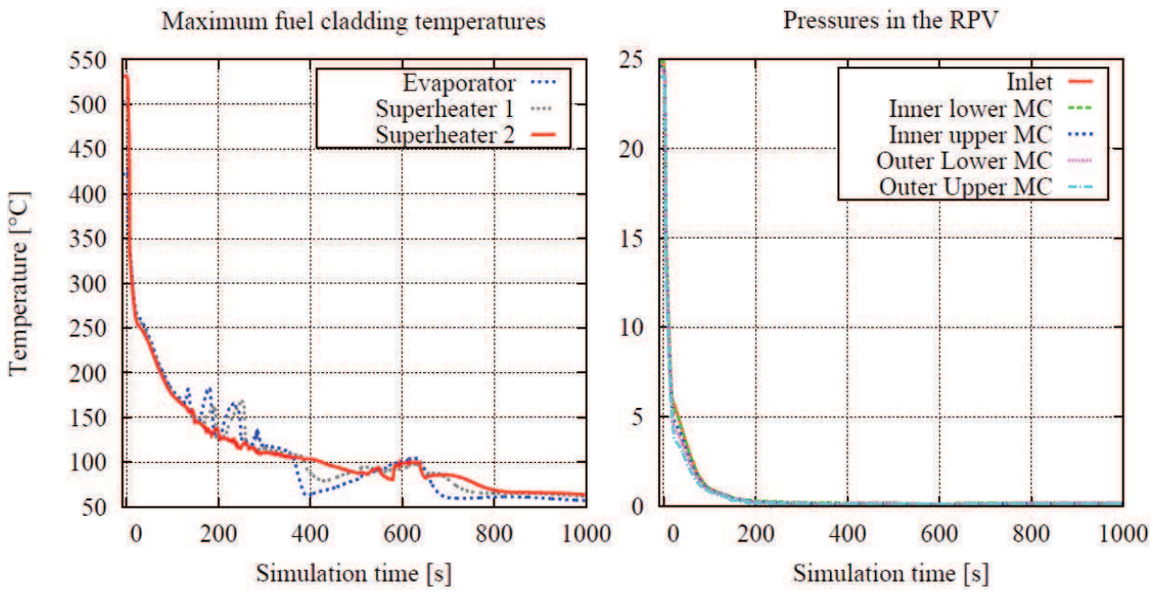


Fig. 5. Results from the HPLWR LB-LOCA simulations: maximum flue cladding temperatures (left) and pressures in different parts of the pressure vessel (right)

10. Conclusion

With modifications described in this paper, the six-equation flow model of the system code APROS has been updated to work near and above the critical point. By using the concept of pseudo saturation enthalpy the two-phase structure can be maintained. The developed model for the forced mass transfer enables the numerically stable and fast transition from pseudo-liquid to pseudo-gas and vice versa. The model includes a selection of friction and heat transfer correlations that the user can choose to be used at supercritical pressures. One deficiency is that at the moment there is not any heat transfer correlation which is able to calculate the impairment of the heat transfer reliably. In simulating the supercritical flows in heated pipes the instabilities due to large density changes is possible. In making simulations with system codes or other simulation tools it is necessary to know the limits of these instabilities. As an example of the HPLWR LOCA simulation proves the developed model can be used for the safety analysis of supercritical-water-cooled reactors.

11. Nomenclature

A	area, flow area (m^2)
β	volumetric coefficient of expansion
f	friction factor
F	friction (N/m^3)
g	acceleration of gravitation (m/s^2)
h	enthalpy (J/kg)
$\dot{m}$	mass flow (kg/s)
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
q	heat flow/volume
Re	Reynolds number
T	temperature (^oC or K)
t	time (s)
u	velocity (m/s)
V	volume (m^3)
x	mass fraction
α	gas volume fraction
ρ	density (kg/m^3)
Γ	mass transfer ($kg/s\ m^3$)
Δt	time step (s)
T	temperature (C)
Δz	mesh spacing in flow direction (m)

Subscripts

b	bulk
col	Colebrook
g	gas
i	interface
k	phase k (either gas or liquid)

kir	Kirillov
l	liquid
lg	evaporation, liquid to gas
p	constant pressure
pc	pseudo critical
sat	saturation
w	wall

Superscript

n	new value

12. References

Ambrosini, W., and Sharabi, M., 2006, Dimensionless Parameters in Stability Analysis of Heated Channels with Fluids at Supercritical Pressures, Proceedings of ICONE 14, 14th International Conference on Nuclear Engineering, July 17-20, 2006, Miami, Florida USA.

Ambrosini, W., and Sharabi, M., 2008, Dimensionless Parameters in Stability Analysis of Heated Channels with Fluids at Supercritical Pressures, *Nuclear Engineering and Design* 238 (2008) 1917–1929.

Bishop, A. A., Sandberg, R.O., Tong, L.S., Forced convection heat transfer to water near critical temperatures and supercritical pressures, Report WCAP–5449, Westinghouse Electrical Corporation, Atomic Power Division (1965).

Fischer, K., Schulenberg, T., Laurien, E., Design of a supercritical water-cooled reactor with a three pass core arrangement. Nuclear Engineering and Design, 239 (2009), pp. 800-812.

Hänninen, M. & Kurki, J. Simulation of flows at supercritical pressures with a two-fluid code. NUTHOS-7: The 7th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety, Seoul, Korea, October 5–9, 2008

Hänninen, M. and Ylijoki, J. The on-dimensional separate two-phase flow model of APROS. Espoo 2008. VTT Tiedotteita – Research Notes.

Jackson, J.D., "A Semi-empirical model of turbulent convective heat transfer to fluids at supercritical pressure, Proceedings of the 16th International Conference on Nuclear Engineering, ICONE16 May 11–15, 2008, Orlando, Florida.

P. Kirillov and V. Grabezhnaya, Heat transfer at supercritical pressures and the onset of deterioration, in Proceedings of ICONE14 (Jul 2006)

P. Kirillov, R. Pomet'ko, A. Smirnov, V. Grabezhnaia, I. Pioro, R. Duffey and H. Khartabil, Experimental Study on Heat Transfer to Supercritical Water Flowing in 1- and 4-m-Long Vertical Tubes, in Proceedings of GLOBAL 2005 (2005)

Kurki, J., Simulation of thermal hydraulics at supercritical pressures with APROS, Thesis for the degree of Master of Science in Technology, Helsinki University of Technology, Department of Engineering Physics and Mathematics, 2008.

Kurki, J. and Hänninen, M., Simulation of flows at supercritical pressures with a two-fluid code, in Proceedings of the 8th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety (NUTHOS-8) (October 2010

Kurki, J. and Seppälä M., Thermal Hydraulic Transient Analysis of the High Performance Light Water Reactor Using APROS and SMABRE , 20th International Conference

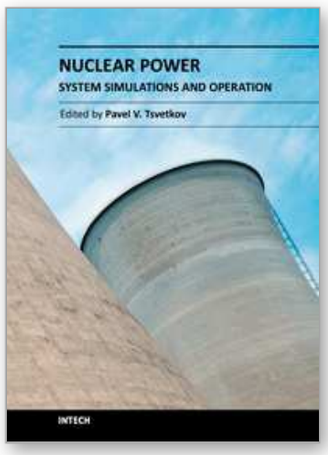
on Structural Mechanics in Reactor Technology (SMiRT 20), Espoo, Finland, August 9 -14, 2009, SMiRT 20 – Division X, Paper 3164

J. Kurki and M. Hänninen, Simulation of a Large-Break Loss of Coolant Accident in the High Performance Light Water Reactor, in Proceedings of IAEA Technical Meeting on 'Heat Transfer, Thermal-Hydraulics and System Design for Supercritical Water Cooled Reactors' (July 2010)

Kurki, J., Computational modeling of a supercritical-Water-Cooled Reactor, Thesis for the degree of Licentiate of Science in Technology, Aalto University, School of Science and Technology, 2010.

Schulenberg, T., Starflinger, J., Heinecke, J., Three pass core design proposal for a high performance light water reactor. Progress in Nuclear Energy, 50 (2008), pp. 526-531.

Watts, M. J., and Chou, C. T., Mixed Convection Heat Transfer to Supercritical Pressure Water, Proceedings of the 7th International Heat Transfer Conference, vol. 3, 495 – 500 (1982)



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At the onset of the 21st century, we are searching for reliable and sustainable energy sources that have a potential to support growing economies developing at accelerated growth rates, technology advances improving quality of life and becoming available to larger and larger populations. The quest for robust sustainable energy supplies meeting the above constraints leads us to the nuclear power technology. Todayâ€™s nuclear reactors are safe and highly efficient energy systems that offer electricity and a multitude of co-generation energy products ranging from potable water to heat for industrial applications. Catastrophic earthquake and tsunami events in Japan resulted in the nuclear accident that forced us to rethink our approach to nuclear safety, requirements and facilitated growing interests in designs, which can withstand natural disasters and avoid catastrophic consequences. This book is one in a series of books on nuclear power published by InTech. It consists of ten chapters on system simulations and operational aspects. Our book does not aim at a complete coverage or a broad range. Instead, the included chapters shine light at existing challenges, solutions and approaches. Authors hope to share ideas and findings so that new ideas and directions can potentially be developed focusing on operational characteristics of nuclear power plants. The consistent thread throughout all chapters is the â€œsystem-thinkingâ€ approach synthesizing provided information and ideas. The book targets everyone with interests in system simulations and nuclear power operational aspects as its potential readership groups - students, researchers and practitioners.

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