IMPROVEMENT OF RELAP5 MODELS FOR CONDENSATION OF STEAM AND STEAM-GAS MIXTURE IN HORIZONTAL AND INCLINED TUBES

P. Kral
UJV Rez, a. s. / Division of Nuclear Safety and Reliability
Hlavni 130, Husinec-Rez, Czech Republic
pavel.kral@ujv.cz

ABSTRACT

The presented work is focused on condensation of steam and steam-gas mixture in horizontal and sloped tubes. Presence of noncondensable gas (NCG) in coolant system of pressurized water reactor (PWR and VVER) has number of potential effects on thermal hydraulics (TH) of the system. One of the major effects is deterioration of heat transfer at steam generator, mainly in the condensation regime. After deep analysis of condensation models in RELAP5 computer code, a set of improvements is proposed. Major modifications are usage of Jaster-Kosky correlation for horizontal condensation and extension of application of horizontal condensation to wider range of tube slopes. Both the original and modified versions of code are assessed against data from separate and integral test facilities. Results show improved capability to predict condensation heat transfer and removal of some unphysical behavior in condensation in volumes with small non-zero slope.

KEYWORDS
Non-condensable gas, thermal hydraulics, condensation, heat transfer, computer code, RELAP5, VVER

1. INTRODUCTION

Condensation on primary side of steam generators (SG) of pressurized water reactors – both PWR and VVER - is a very important heat transfer mode in transient and accident conditions. So far, most effort in this field has been focused on condensation in vertical tubes. Condensation in horizontal and sloped tubes is however also important. The horizontal or slightly sloped tubes are used in horizontal steam generators, some passive safety systems, number of heat exchangers etc.

Further important issue is deterioration of steam condensation in presence of noncondensable gas. The initially homogeneous mixture of steam and gas changes due to condensation of steam to non-homogeneous mixture with substantially higher concentration of noncondensable gas by the condensate-vapor interface – creating an insulation layer. Prediction of condensation of steam-gas mixture is therefore a challenging task for all TH computer codes.

The presented work is focused on condensation of steam and steam-gas mixture in horizontal and sloped tubes, improvements and extended validation of condensation models of RELAP5 computer codes [1], and on improved computational capability for safety analyses of VVER with horizontal steam generators. However, substantial part of findings and results are general and applicable also to other systems.

2. CONDENSATION OF STEAM AND STEAM-GAS MIXTURE IN VERTICAL AND HORIZONTAL TUBES AS MODELED IN RELAP5

The system TH computer code RELAP5 is a world-wide used computational tool for safety analyses of transients and accidents in light water reactors (LWR) developed under US NRC sponsorship.

The default RELAP5 [1] condensation model for vertical and inclined surfaces uses the maximum of Nusselt laminar model [2] and Shah turbulent model [3]. For strictly horizontal walls, Chato modification of Nusselt is used [4]. The Colburn-Hougen iterative diffusion method [5] is used to solve condensation heat transfer in presence of noncondensable gas. See the overall computational algorithm in Figure 1 below. A more detailed description of equations used follows.

The RELAP5 [1] calculates condensation heat transfer coefficients (HTC) based on filmwise condensation model. The method of calculating the heat transfer coefficient h_c is given below. Once the h_c is known, it is used to calculate the total heat flux:

$$q_t^{"} = h_c\left(T_w - T_{sppb}\right) \tag{1}$$

where q_t“ is total heat flux by condensation, h_c is the heat transfer coefficient, T_w is wall temperature and T_{sppb} is saturation temperature based on partial pressure in the bulk.

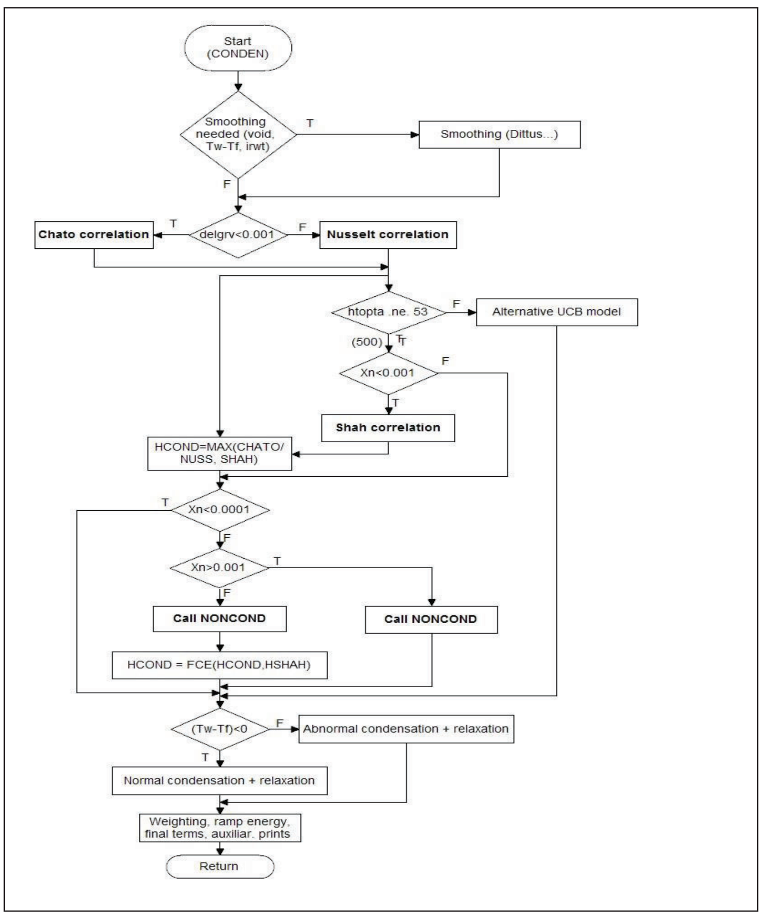


Figure 1. Algorithm of condensation calculation in RELAP5

Because RELAP5 is a two-fluid code, the liquid and the gas can both theoretically exchange energy with the wall. Although film condensation is the only condensation mode considered, currently RELAP5 allows both heat flux to liquid and to gas. The heat flux to liquid is defined as follows:

$$q_f^{"} = h_c \left(T_w - T_f\right) \tag{2}$$

where q_t" is condensation heat flux to liquid, h_c is the condensation heat transfer coefficient, T_w is wall temperature and T_f is bulk liquid temperature.

The gas to wall heat flux is the difference between the total heat flux q_t" and the liquid to wall heat flux q_f". The interfacial mass transfer term used in RELAP5 continuity equation comprises mass transfer at the wall and transfer in the bulk. The term for mass transfer near the wall comprises only of the heat flux from the gas to the wall.

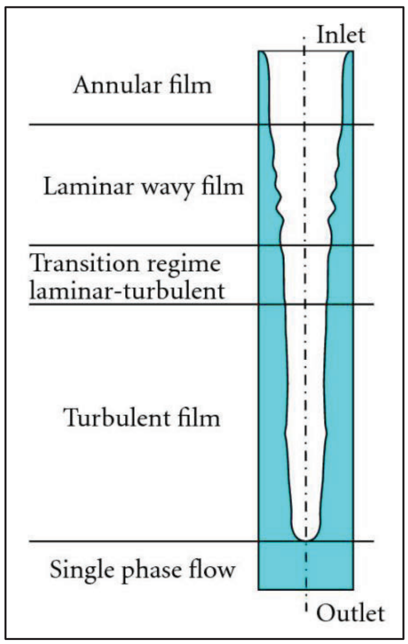


Figure 2. Condensation at vertical wall with laminar and turbulent film region

The basic approach of RELAP5 to determination of condensation heat transfer coefficient is selecting of maximum from Nusselt laminar model [2] and Shah turbulent model [3]:

$$h_c = \max(h_{nusselt}, h_{shah}) \tag{3}$$

2.1. Nusselt Model for Laminar Film Condensation at Vertical Wall

The Nusselt expression for laminar film condensation [2] at vertical surfaces uses the film thickness, δ, as the key parameter instead of the temperature difference:

$$h_{c,nusselt} = \frac{k_f}{\delta} \tag{4}$$

where k_f is liquid conductivity and the film thickness δ is defined by this relation:

$$\delta = \left(\frac{3\mu_f \Gamma}{g\rho_f \Delta\rho} \right)^{\frac{1}{3}} \tag{5}$$

where μ_f is liquid viscosity, Γ is liquid mass flow rate per unit periphery, g is gravitational constant ρ_f is liquid density and $\Delta\rho$ is difference between liquid and gas bulk density.

Then the resulting Nusselt's expression for condensation heat transfer coefficient is the following:

$$h_{c,nusselt} = \left(\frac{g\rho_f \Delta\rho k_f^{\ 3}}{3\mu_f \Gamma} \right)^{\frac{1}{3}} \tag{6}$$

2.2. Shah Model for Turbulent Film Condensation

The basic formula in Shah model for turbulent film condensation at both vertical and horizontal surfaces:

$$h_{c,shah} = h_{sf} \left(1 + \frac{3{,}8}{Z^{0{,}95}} \right) \tag{7}$$

where h_{sf} is superficial heat transfer coefficient and parameter Z reflects influence of static vapor quality and reduced bulk pressure (for more details see [1] or [3]).

As the Shah model for turbulent film condensation is not modified, the paper will not describe it in detail.

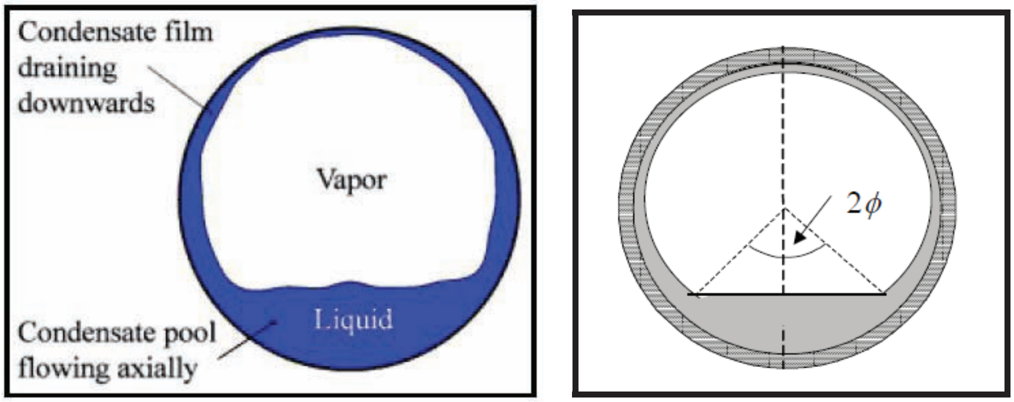
2.3. Chato Modification of Laminar Film Condensation Model for Horizontal Tubes

Condensation in horizontal or sloped tubes is more complex thermal-hydraulic process than condensation in a vertical tube. Whereas in case of vertical tube, the condensate film flows predominantly in axial direction (1D problem), in case of horizontal tube the condensate film flows predominantly in circumferential direction (potentially inclined due to axial drag of steam) and the condensate in bottom "pool" flows in purely axial direction.

Chato [4] developed a modification to the standard Nusselt formulation [2] which applies to laminar condensation inside horizontal tube. It is assumed that the liquid film collects on the upper surfaces, drains to the tube bottom, and collects with negligible vapor shear. The condensate drains out one end because of a hydraulic gradient. The Chato formula for condensation HTC looks as follows:

$$h_{c,chato} = F \left(\frac{g\rho_f \Delta\rho h_{fgb} k_f^3}{D_h \mu_f \left(T_{sppb} - T_w \right)} \right)^{\frac{1}{4}} \tag{8}$$

where F is a correction term reflecting liquid level in the tube bottom, g is gravitational constant, ρ_f is liquid density, $\Delta\rho$ is difference between liquid and gas bulk density, k_f is liquid conductivity, D_h is hydraulic diameter, μ_f is liquid viscosity, T_{sppb} is saturation temperature based on steam partial pressure in the bulk, and T_w is the wall temperature.



(a) (b)

Figure 3. Laminar film condensation in horizontal tube

The *F* term in equation (8) corrects the condensation heat transfer for the liquid level in the tube bottom (reducing the effective condensing wall surface) with the form:

$$F = \left(1 - \frac{\Phi}{\pi}\right) F' \tag{9}$$

The angle *2Φ* corresponds to the angle subtended from the tube center to the chord forming the liquid level (see Figure 3 b). The values for *F´* range in magnitude upward from 0.725, where 2Φ = zero. The angle 2Φ can be determined from the following expression:

$$\alpha_f = \frac{\Phi - 0.5\sin 2\Phi}{\pi} \tag{10}$$

The analytical work indicates that the heat transfer through the bottom layer was less than 2.5% of the total for angles of 2Φ between 90 and 170 degrees and was therefore neglected in the correlation. Chato suggests a mean value of F = 0.296 which corresponds to Φ = 120^{o}. This constant value is used in RELAP5 [1]. The Chato correlation was tested from horizontal to the inclined angles of about 37 degrees with reasonable results [4]. However, in RELAP5, the Chato model of horizontal condensation is applied only to strictly horizontal volumes (with elevation parameters delgrv < 0.001).

2.4. Colburn-Hougen Diffusion Method for Condensation with Noncondensable

Prediction of condensation in presence of noncondensable gas is in RELAP5 done by help of the Colburn-Hougen diffusion method [5]. The Colburn-Hougen diffusion calculation involves an iterative method to solve for the temperature at the interface between the steam and water film.

The method is based on the principle that the amount of heat transferred by condensing vapor to the liquid-vapor interface by diffusing through the noncondensable gas film is equal to the heat transferred through the condensate film:

$$h_c\left(T_{vi} - T_w\right) = h_m h_{fgb} \rho_{vb} \ln\left(\frac{1 - \frac{P_{vi}}{P}}{1 - \frac{P_{vb}}{P}}\right) \tag{11}$$

where T_{vi} is vapor temperature at the liquid-gas-vapor interface, T_w is the wall temperature, h_m is mass transfer coefficient, h_{fgb} is difference of steam and liquid enthalpy in the bulk, P_{vi} is partial pressure of steam at liquid-gas-vapor interface, P_{vb} is steam partial pressure in the bulk, ρ_{vb} is saturation vapor density at P_{vb}, and P is the total pressure. From this energy conservation principle, the interface pressure and temperature (see Figure 4) is determined by iterations. The heat transfer rate then is then determined.

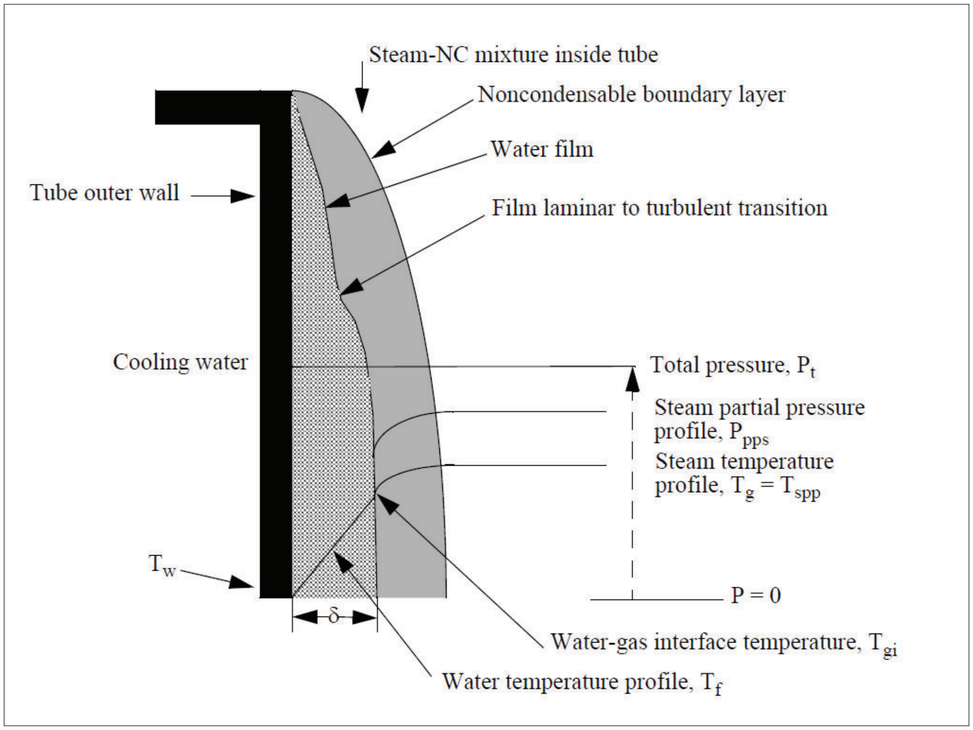


Figure 4. Film condensation in presence of noncondensable gas

3. PROPOSED SET OF MODIFICATIONS IN RELAP5 CONDENSATION MODEL FOR HORIZONTAL AND SLOPED TUBES

Based on the deep analysis of RELAP5 condensation model (description in manual plus source code) and results of calculations of separate effect tests the following modifications were proposed:

A. Replacement of Chato correlation for horizontal condensation [4] by Jaster and Kosky modification [6], which instead of constant F (see above) uses a function of local void fraction.

B. Extension usage of horizontal condensation model from strictly horizontal volumes also to inclined volumes.

C. Change in parameter for decision between horizontal and vertical condensation models from elevation parameter „delgrv“ to slope parameters „sing“.

D. Optional relaxation for inlet volume of condensation tube (weighting between condensation models with/without Colburn-Hougen to reflect not yet fully developed NCG concentration profile at the tube inlet).

The Chato correlation for horizontal condensation [4] as programmed in RELAP5 [1] is using constant parameter F (value 0.296 used) for degradation of effective condensation wall surface by pool of condensate in bottom part of tube. Jaster and Kosky [6] proposed modification of this correlation which instead of constant F uses a function of local void fraction. This approach is more flexible and suitable for an advanced 6-equation TH code, which for each control volume evaluates the void fraction α as one of the main 6 variables. Jaster and Kosky correlation has the following form:

$$h_{c,\,jaster-kosky} = 0{,}725\alpha^{3/4}\left(\frac{g\rho_f\,\Delta\rho h_{fgb}k_f^3}{D_h\mu_f\left(T_{sppb}-T_w\right)}\right)^{\frac{1}{4}} \tag{12}$$

where α is a void fraction, g is gravitational constant, ρ_f is liquid density, $\Delta\rho$ is difference between liquid and gas bulk density, k_f is liquid conductivity, D_h is hydraulic diameter, μ_f is liquid viscosity, T_{sppb} is saturation temperature based on steam partial pressure in the bulk, and T_w is the wall temperature.

The horizontal condensation model as programmed in RELAP5 is used only in strictly horizontal volumes, for which the elevation parameter delgrv < 0.001 (corresponds to slope 0.005° for 1 m long volume). As soon as the slope is higher (e.g. 0.01°) the vertical condensation model is used – which is not the best approach and leads to unphysical results for small slopes as will be demonstrated in chapter 4.

Such arguable usage of vertical condensation model for small slope tubes is potentially problematic for any horizontal heat exchangers (including horizontal steam generators of VVER). As nearly all horizontal SG's and heat exchangers use a small drainage slope. As soon as the analyst models the exact slope of the "horizontal" tubes, the code could produce wrong results in condensation mode.

Several options are possible when extending the slope range, for which the horizontal condensation model should be applied, from strictly horizontal volumes (original RELAP5 approach):

a) Usage of horizontal condensation model in volumes with slope θ < 5°
(the smallest change from original RELAP5 approach, but covering small drainage slopes of all horizontal heat exchangers, including VVER steam generators);
b) Usage of horizontal condensation model in volumes with slope θ < 37°
(slope range for which the original horizontal condensation model [4] was validated);
c) Usage of horizontal condensation model in volumes with slope θ < 45°
(this slope would be most consistent with RELAP5 volume flow regime map, as 45° is boundary between vertical and horizontal volume flow regime maps; the horizontal volume flow regime map contains among others the "horizontal stratified flow" regime);
d) Usage of horizontal condensation model in volumes with slope θ < 30°, vertical condensation model in volumes with slope θ > 60°, and interpolation for volumes with slope in range 30-60°.

In the modified RELAP5 version used for validation calculation presented here the variant "c" was chosen (with boundary slope 45°). However, from the point of view of application to horizontal SG of VVER (with tubes slope approximately 0.5°), all four variants are equal.

4. ASSESSMENT OF ORIGINAL AND MODIFIED RELAP5 ON COTINCO DATA

Caruso et al performed series of tests at the COTINCO separate effect test facility in 1999-2001 [7][8][9] and then at the ITACSO facility in 2003 [10], both installed in the University of Roma "La Sapienza". The tests were focused at the steam and air-steam condensation inside horizontal and inclined tubes.

4.1. Description of COTINCO Separate Effect Test

The COTINCO experimental facility [7] has been designed to investigate the heat transfer performance of horizontal and inclined tubes with steam and air-steam mixture flowing inside with condensation. The main components of the experimental facility are the following:

- Atmospheric steam generator, electrically heated, with a gross power ranging from 375 W to a maximum of 6 kW;
- Auxiliary air system feeding the test section with a fixed air flow rate, to perform tests in steady or quasi-steady conditions;
- Mixing tank, where the air-steam mixture is generated, with a volume of about 1 m^3;
- Condensation test section, manufactured with a 22/25 mm internal/external diameter stainless steel tube, 1.5 m long. The air-steam mixture flows inside the tube. The cooling water flows through an annular zone realized with an external tube of 32 mm internal diameter;
- Cooling system, with water tank, pumps, heaters and a water softener;
- Instrumentation and data acquisition system.

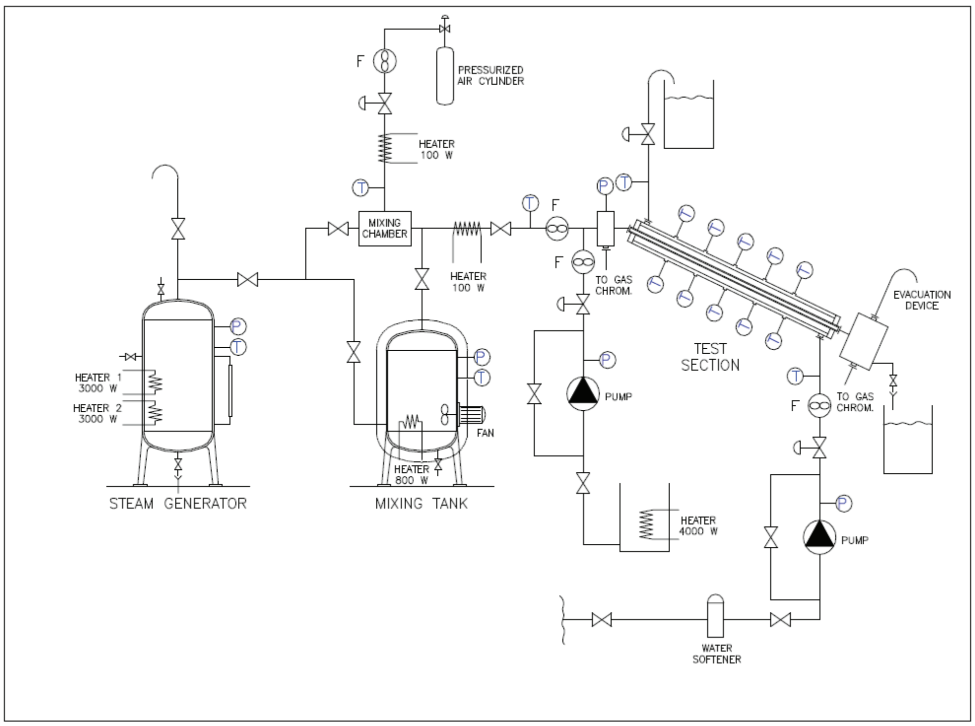


Figure 5. COTINCO experimental loop

The available power is 6 kW, but the test section has been designed to operate in the range 3 ÷ 4 kW. This condition allows to have enough power to carry out tests with higher power level. The heat losses in the steam loop are very low (less than 0.2 kW) and they have been characterized through an integral mass measurement of the condensate at the inlet of the instrumented tube before the assembling. Heat losses in the cooling side of the test section are negligible, due to the low coolant temperatures.

The test section (condensation tube) used for measurement of the heat transfer coefficients related to steam-air mixture had been designed according to the following specifications:

- Max available power: 6 kW
- Operating power: 3 - 4 kW

- Design pressure: 1 ate
- Operating pressure: 0 ate
- Air concentration: 0 - 100 %
- Steam-air mixture inside tube (0.85 to 5.55 kg/m^2s)
- External coolant in the annulus: water (with temperature increase 5 - 10 °C)
- Average heat flux: from 7500 to 136,000 W/m^2.

Table I. Matrix of COTINCO Condensation Tests

Inclin. to horizontal [°]	Qsteam 10^3[m^3/s]	Steam vel. [m/s]	Qair (SLPM)	% air (mass)
0°/15°/30°/45°	1.6	4.2	0	0%
0°/15°/30°/45°	1.6	4.2	1	2%
0°/15°/30°/45°	1.6	4.2	2	4%
0°/15°/30°/45°	1.6	4.2	5	10%
0°/15°/30°/45°	1.6	4.2	10	20%
0°/15°/30°/45°	1.6	4.2	15	25%
0°/15°/30°/45°	1.2	3.15	15	30%
0°/15°/30°/45°	0.777	2.0	15	40%
0°/15°/30°/45°	0.388	1.0	15	60%

In the Table I above, a matrix of COTINCO tests is shown [7]. Figures 6 and 7 below show measured dependence of heat transfer coefficient on air concentration and on slope of the tube and typical temperature profiles alongside test section of the condensation tube, respectively.

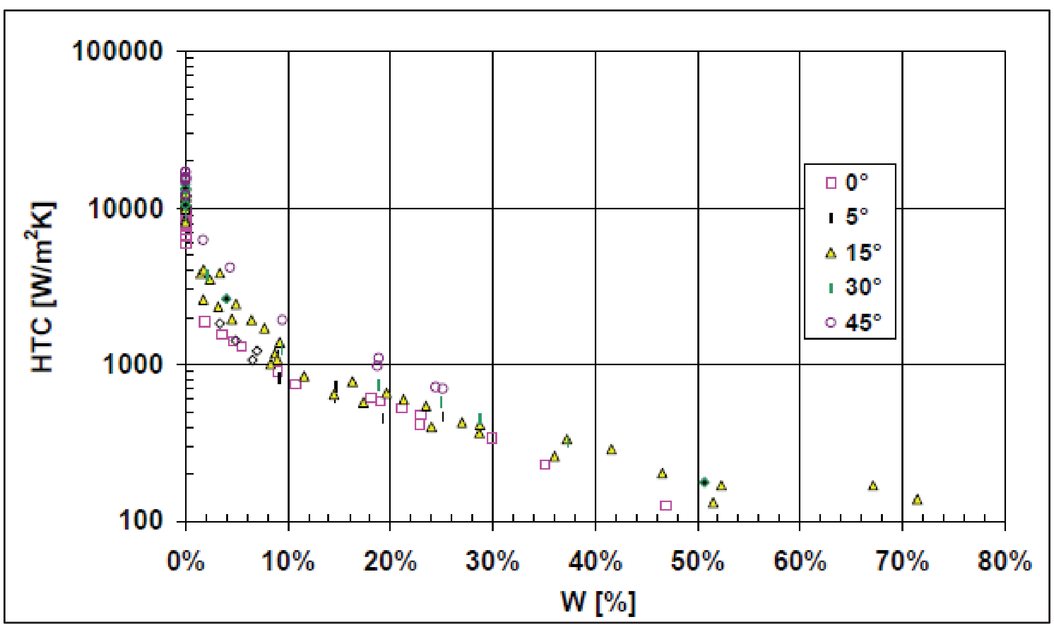


Figure 6. Measured condensation HTC – effect of air mass fraction

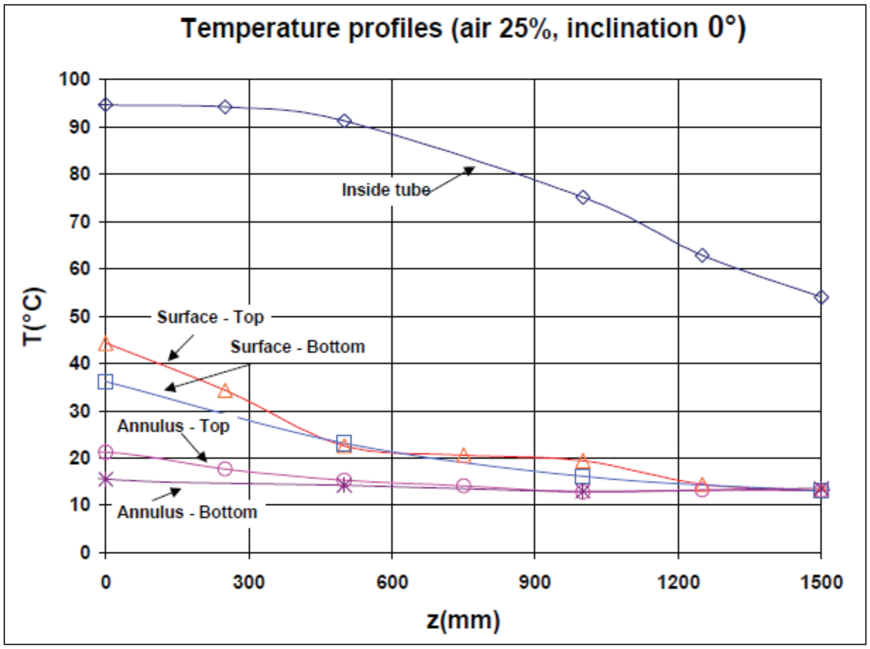


Figure 7. Temperature profiles alongside condensation tube

4.2. RELAP5 Model of COTINCO and Results of Calculations

During development of COTINCO input model for RELAP5, the nodalization (discretization) shown in Figure 8 below was selected. The condensing tube (test section) was modeled by 15 control volumes, each 0.1m long. The cooling annulus was discretized in the same way.

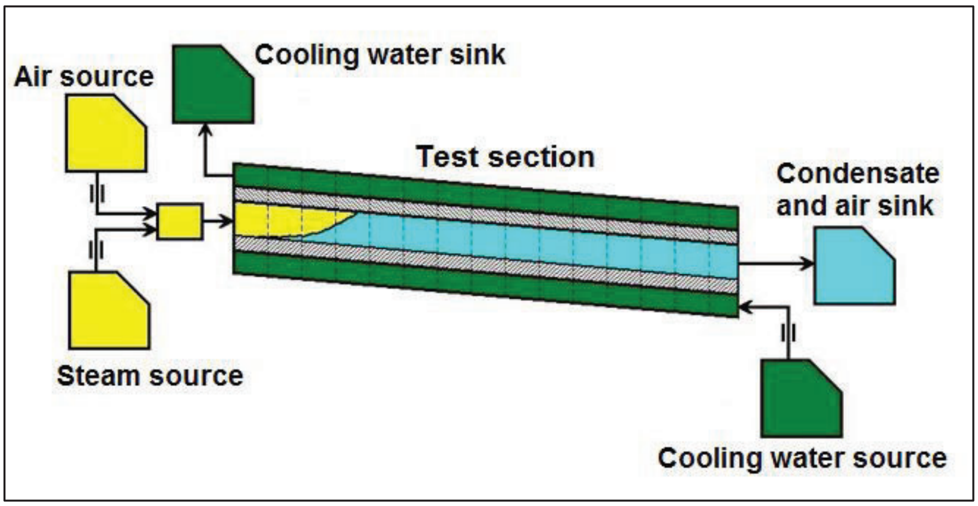


Figure 8. Nodalization of COTINCO input model for RELAP5

The first set of RELAP5 assessment calculations was focused on **condensation of pure steam and effect of slope** of the condensing tube [8]. The velocity of steam at the tube inlet was 4.2 m/s. Measured data are available for slopes 0°, -15°, -30°, and -45°. The calculations were done for slopes 1°, 0°, -1°, -5°, -15°, -30°, and -45° to test more in detail code performance.

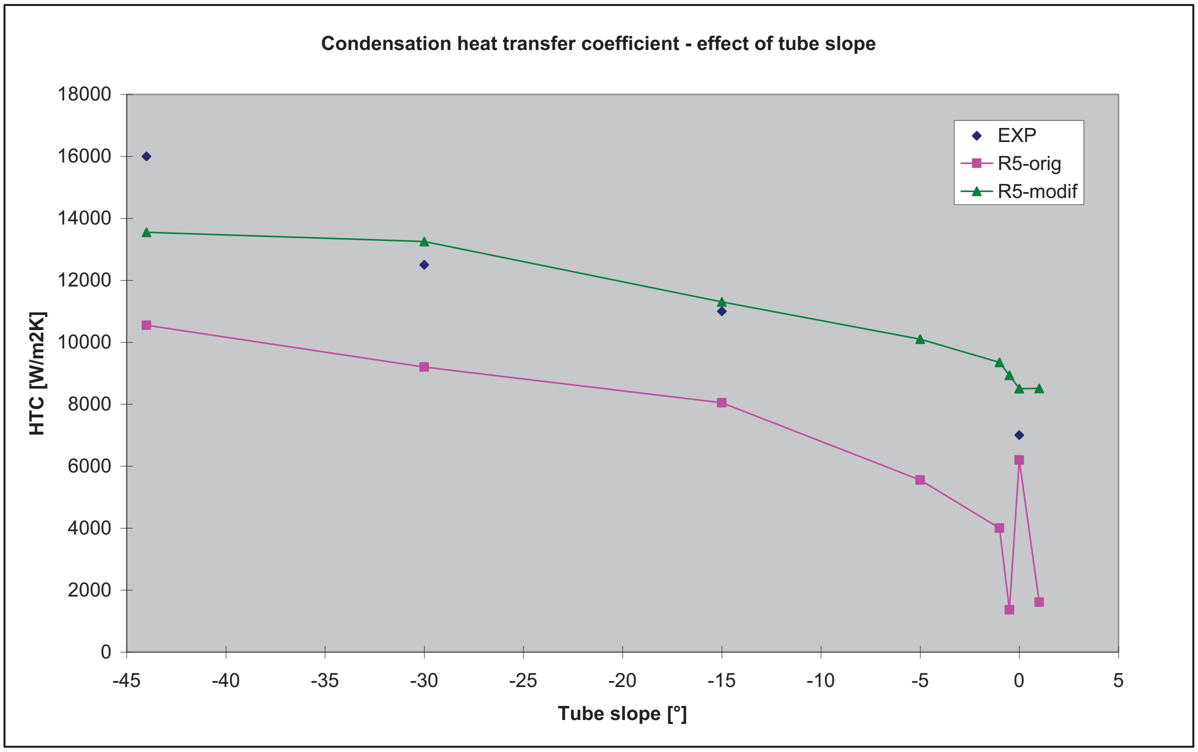


Figure 9. Measured and calculated HTC – effect of tube slope

Results of measurements show increase of average heat transfer coefficient with increasing slope (declination angle) of the tube from 0 to -45° (Figure 9). Calculations with original version of RELAP5 lead to underprediction of the condensation HTC and show unphysical results (drop of HTC) for small nonzero slopes. It is consequence of usage of vertical condensation model for these angles (discussed above in chapters 2 and 3). Calculations with modified version of RELAP5 gives better results and agreement with measured data, plus no local drop of HTC for small nonzero slopes. For the available data points – i.e. without HTC for the small nonzero angles (where the experimental data are not available) - the RELAP5 modification leads to reduction of standard deviation from 3533 to 1492 W/m^2K.

The second set of RELAP5 recalculations of COTINCO data [9] was focused on **condensation length in tests with pure steam condensation** (various steam flow rates from 0.0005 to 0.00225 kg/s and various tube slopes from 0° to -45°). Agreement between experimental and computation results was after modification of RELAP5 condensation model improved from 0.304 m to 0.112 m (standard deviation). See the results of calculation with original and modified RELAP5 shown in Figure 10 and 11, respectively. The given set of experimental data [8] doesn't show any strong effect of tube inclination on condensation length, so just the average values for each inlet steam flow were used for comparison in Figure 10 and 11.

The last set of RELAP5 assessment calculation used COTINCO measurement [7] of **steam-air condensation with various air concentrations**. The air mass fraction (air quality, X_{air}) at tube entrance was 2%, 4%, 10%, 20% a 25% and the tube slope was -15°. Comparison of experimental data and calculation results with original and modified RELAP5 are shown in Figure 12. Measured and predicted average HTC are in perfect agreement at air quality about 10 %. For lower qualities code underpredicts HTC, for higher qualities code overpredicts HTC. Modification of RELAP5 condensation model improved agreement in region of lower gas qualities (X_{air} 2÷10%) where the standard deviation was reduced from 550 to 229 W/m^2K.

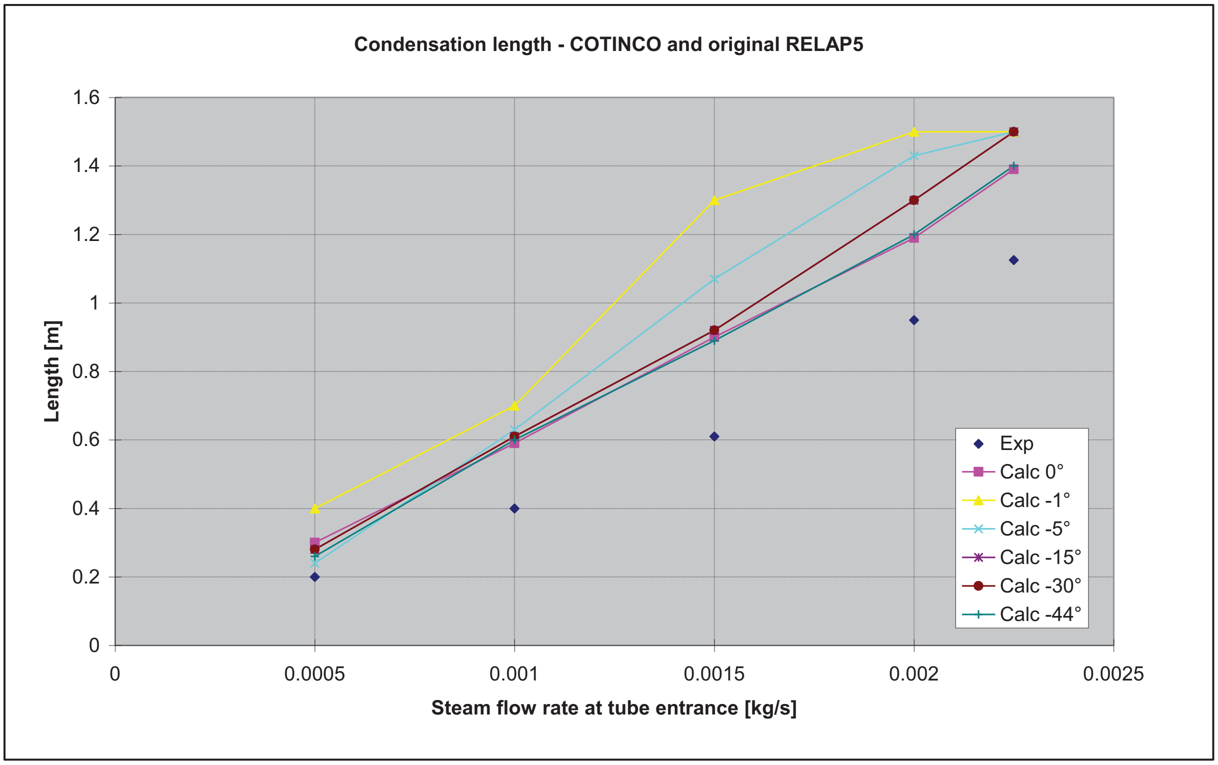


Figure 10. Condensation length for various steam flow – test and original RELAP5

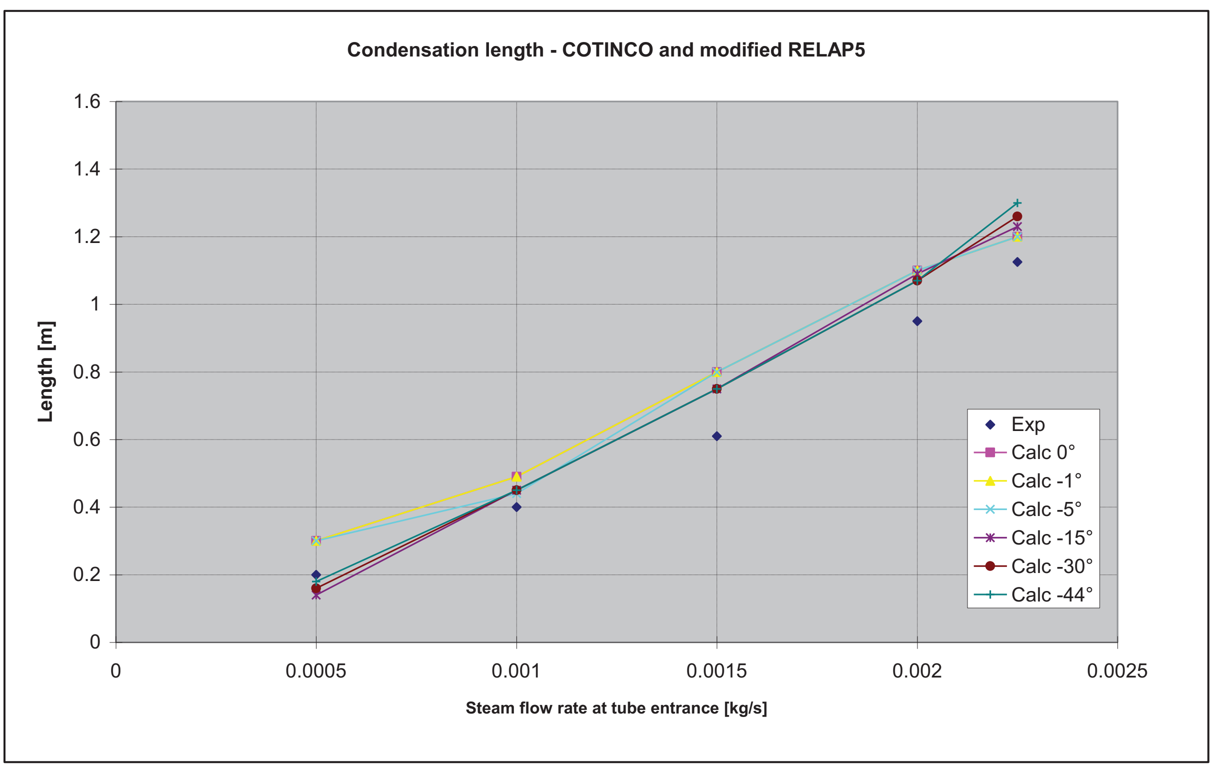


Figure 11. Condensation length for various steam flow – test and modified RELAP5

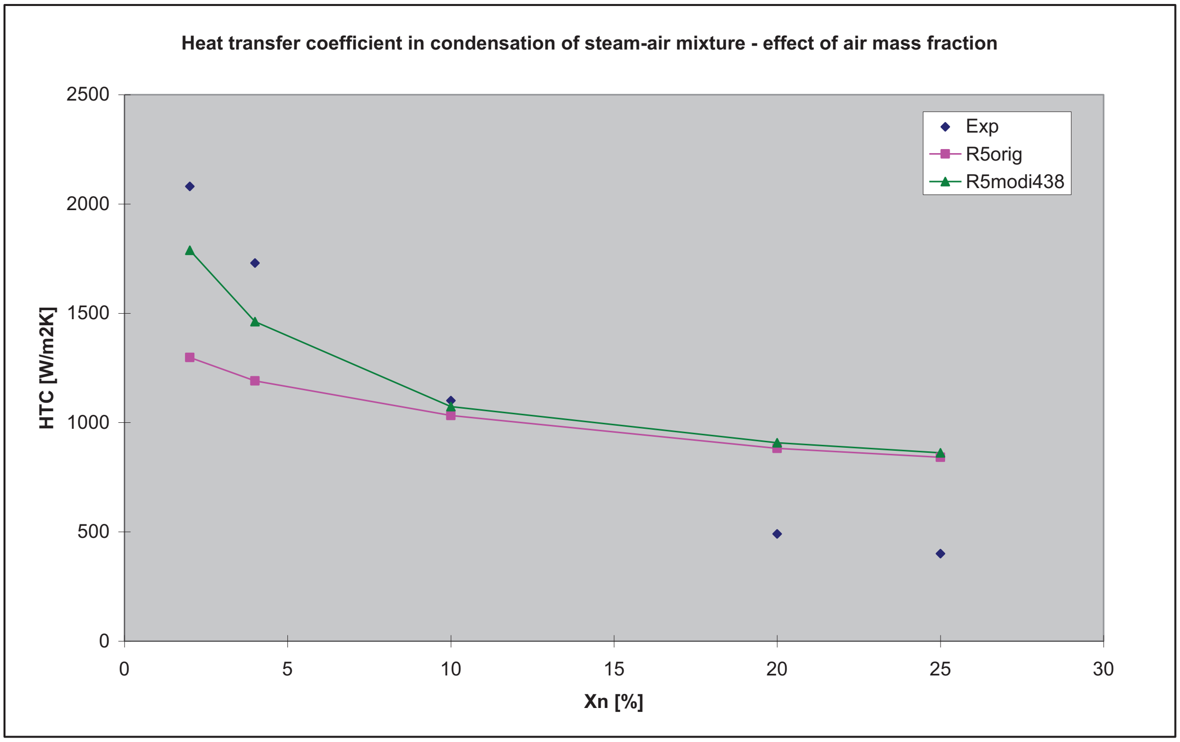


Figure 12. Measured and calculated HTC – effect of air mass fraction

4.3. Further Assessment of Modified RELAP5

Limited scope of this paper does not allow presenting of all results from the assessment and validation of modified RELAP5 condensation models. Besides the code validation against COTINCO tests (presented above), the following validation exercises were done:

a) Validation calculations against condensation tests performed at ITASCO facility [10][13]
Tests focused on local heat transfer coefficient during steam-air condensation.

b) Validation calculations against data from PMK integral test facility [11][12]
Recalculation of test T3.1 medium break loss-of-coolant (LOCA) from shutdown conditions with nitrogen in PRZ, comparison of results of calculation with original and modified RELAP5.

c) Test calculations with model of PMK facility
Analysis of artificial small-break LOCA scenario without HPIS and with secondary steam dump and condensation in SG, with original and modified RELAP5.

d) Comparison calculations with SG model.
New test calculations with separate model of horizontal steam generator. Calculations with fixed and with flowing boundary conditions, with original and modified RELAP5.

Assessment against ITASCO tests proved improved capabilities of modified RELAP5 to predict local heat transfer coefficient during steam-air condensation. Validation analyses with model of PMK integral test facility [12] and with separate SG model showed stability of modified version and improved prediction of condensation in horizontal SG (although the differences between original and modified RELAP5 were not so remarkable like in calculations of separate effect tests).

5. CONCLUSIONS

The paper describes work on assessment and modification of condensation model of RELAP5 computer code. The effort is focused on condensation of steam and steam-gas mixture in horizontal and sloped tubes. Introductory deep analysis of RELAP5 condensation model resulted in proposal of set of modifications of this model – the main modifications are the usage of Jaster-Kosky correlation for horizontal condensation (instead of Chato correlation) and extension of application of horizontal condensation models to wider range of slopes. Both original and modified version of the code is assessed against experimental data from separate effect test facilities COTINCO and ITASCO. The results show improved capability to predict condensation heat transfer. Also the unphysical drop in predicted condensation heat transfer coefficient for small non-zero slopes detected in original RELAP5 was removed in modified version. Modified RELAP5 is also tested in calculations of integral tests – medium and small break LOCA tests with model of PMK facility and test calculations with separate SG model. Also the results from integral tests prove improved performance in prediction of condensation heat transfer and good stability of the modified RELAP5 code.

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