Activities of passive cooling applications and simulation of innovative nuclear power plant design

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Abstract. This paper gives a general insight on activities of the Turkish Atomic Energy Authority (TAEA) concerning passive cooling applications and simulation of innovative nuclear power plant design. The condensation mode of heat transfer plays an important role for the passive heat removal application in advanced water-cooled reactor systems. But it is well understood that the presence of noncondesable (NC) gases can greatly inhibit the condensation process due to the build up of NC gas concentration at the liquid/gas interface. The isolation condenser of passive containment cooling system of the simplified boiling water reactors is a typical application area of in-tube condensation in the presence of NC. The test matrix of the experimental investigation undertaken at the METU-CTF test facility (Middle East Technical University, Ankara) covers the range of parameters; P_n (system pressure) : 2-6 bar, Re_v (vapor Reynolds number): 45000-94000, and X_i (air mass fraction): 0-52%. This experimental study is supplemented by a theoretical investigation concerning the effect of mixture flow rate on film turbulence and air mass diffusion concepts. Recently, TAEA participated to an international standard problem (OECD ISP-42) which covers a set of simulation of PANDA test facility (Paul Scherrer Institut-Switzerland) for six different phases including different natural circulation modes. The concept of condensation in the presence of air plays an important role for performance of heat exchangers, designed for passive containment cooling, which in turn affect the natural circulation behaviour in PANDA systems.

1. INTRODUCTION

Nuclear energy is one of the options presently available to cope with energy needs along the forthcoming century. This challenge is requiring a tremendous effort to assure nuclear energy competence in terms of economics and safety with respect to the other potential sources of energy. In the case of water cooled power reactors, new advanced designs have been proposed of either an evolutionary or a passive type, the latter being particularly appealing for using natural forces to carry out safety functions under the most adverse conditions posed by hypothetical accidents. In this regard containment of passive reactors is to be equipped with what has been called Passive Containment Cooling Systems (PCCS).

PCCS's features depend on specific designs. However, most of them share their reliance on steam condensation to mitigate long term pressure rise in containment. New boundary conditions and device geometries prompted renewed to investigate steam condensation to eventually demonstrate PCCS's capability to meet their goals. As a result, experimental and analytical programs were launched worldwide, often on the basis of a fruitful international co-operation [1].

Concepts of passive safety systems with no active components have been investigated for new generation light water reactors [2]. The primary objectives of the passive design features are to simplify the design, which assures the minimised demand on operator, and to improve plant safety. To accomplish these features the operating principles of passive safety systems should be well understood by an experimental validation program. Such validation programs are also important for the assessment of advanced computer codes, which are currently used for design and licensing.

In an application, the proposed advanced passive boiling water reactor design, simplified boiling water reactor (SBWR), utilises as a main component of the passive containment cooling systems (PCCS) the isolation condenser (IC). The function of the IC is to provide a passive heat exchanger for the removal of the reactor coolant system sensible heat, and core decay heat to a reservoir of water within the containment. In performing this function, the IC must have the capability to remove sufficient energy from the reactor containment in order to prevent the containment from exceeding design pressure shortly following design basis event and to significantly reduce containment pressure in the longer run [3]. However, it is well established that the presence of noncondensable (NC) gases in vapors can greatly inhibit the condensation process. The mass transfer resistance to condensation results from a build-up of NC gas concentration at the liquid/gas interface leading to a decrease in the corresponding vapor partial pressure and thus the interface temperature at which condensation occurs [3]. As a result, reduction in heat transfer rate is unavoidable with respect to the pure condensation case.

A part of the long-term research and development efforts of the Turkish Atomic Energy Authority (TAEA) is planned to concentrate on passive cooling systems. In this paper, a general insight on activities of the TAEA concerning condensation in the presence of air is given. Moreover, TAEA participated to an international standard problem (OECD/NEA ISP-42) which covers a set of simulations of PANDA test facility, which is the scaled model of SBWR for different phases of natural circulation modes. The concept of condensation in the presence of air plays an important role for the performance of heat exchangers, designed for passive containment cooling, which in turn affect the natural circulation behaviour in such innovative systems.

2. EXPERIMENTAL STUDY

The test facility named as Middle East Technical University Condensation Test Facility (METU-CTF) was installed at the Mechanical Engineering Department of METU. The experimental set up consisting of an open steam or steam/gas system and open cooling water system is depicted in the flow diagram of Figure 1 [4].

Steam is generated in a boiler (1.6 m high, 0.45 m ID) by using four immersion type sheathed electrical heaters. Three of these heaters have a nominal power of 10 kW each and the fourth one has a power of 7.5 kW at 380 V. All the heaters can be individually controlled by switching on or off. The boiler tank was designed to withstand an internal pressure of 15 bar, at T = $20\,^{0}C$, and was tested at this pressure. The maximum operating pressure of the tank is 10 bar. To ensure dry steam at the exit of the boiler, a mechanical separator directly connected to the exit nozzle was installed. The boiler tank was thermally insulated to reduce the environmental heat loss.

Compressed air can be supplied either to the boiler tank or to the steam line via nozzle after the orifice meter on the horizontal part of the pipe, which connects the boiler and the test section.

The pipe connecting the boiler tank and the test section has a length of approximately 2 m and an ID of 38.1 mm. The pipe was connected to the boiler tank via an isolation valve. This isolation valve is used to isolate the boiler until inside pressure of the tank is increased to a predetermined level.

The test section is a heat exchanger of countercurrent type, that is steam or steam/gas mixture flows downward inside the condenser tube and cooling water flows upward inside the jacket pipe.

The condenser tube consists of a 2.15 m long seamless stainless steel tube with 33/39 mm ID/OD. The jacket pipe surrounding the condenser tube is made of sheet iron and has a length of 2.133 m and 81.2/89 mm ID/OD.

A total of 13 holes were drilled with an angle of 30^0 at different elevations along the condenser tube length to fix the thermocouples for inner wall temperature measurements. Similarly, 15 holes were drilled radially at different elevations for installation of the thermocouples to be used for cooling water temperature measurements. The jacket pipe was thermally insulated to reduce environmental heat loss. Ten thermocouples were fixed to a 2 mm diameter Inconel guide wire and installed at the central temperature measurements.

The experimental text matrix has been constituted by pure steam and steam/air mixture runs and the effect of NC gas has been analyzed by comparing the pure steam runs with mixture runs with respect the temperature, heat flux, air mass fraction, and film Reynolds number. The range of the measured parameters; $P_n = 2\text{-}6$ bars, $Re_v = 45{,}000\text{-}94{,}000$, and $X_i = 0\ \%\text{-}52\%$.

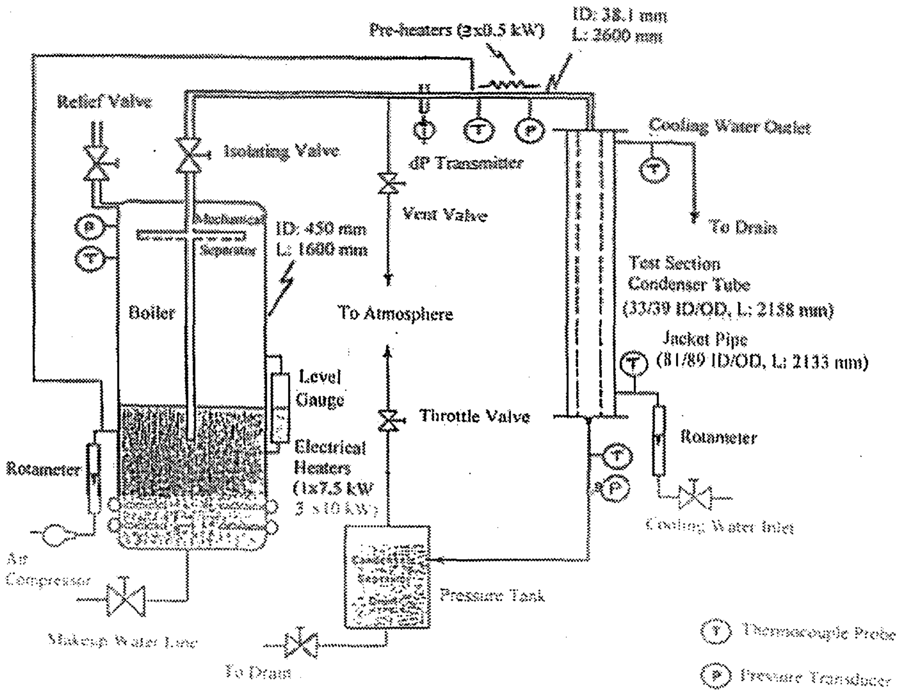

FIG. 1. Schematic view of the METU-CTF [4]

3. THEORETICAL STUDIES

Although many of the theoretical studies have been performed to investigate the effect of NC gases on steam condensation, in recent years studies have been prosecuted by simple correlations such as the correlation introduced by UCB. In this correlation, the local heat transfer coefficient is expressed in the form of a "degradation factor" defined as the ratio of the experimental heat transfer coefficient to a reference, pure steam, heat transfer coefficient. The reference heat transfer coefficient is calculated from Nusselt theory. Moreover, the enhancement of heat transfer coefficient due to the shear stress of the gas on liquid film is considered, f_{shear}, and conveyed to the correlation. The other effects enhancing the condensation heat transfer coefficient are also taking into account, f_{others}, and are correlated in terms of liquid side Reynolds number, Re_L. The suppression of the condensation heat transfer coefficient by the accumulation of the NC gas at the interface is clarified and denoted as f_2. In this present study, both the enhancement and the suppression factors given in UCB formulation are modified by considering mixture side Reynolds number and the Sherwood number defining the radial concentration gradient of NC gas respectively.

f Type Correlation Modified by Sherwood Number

$$\mathbf{f} = \mathbf{f_1 . f_2} \tag{1}$$

where

f is the degradation factor, f_1 is the enhancement factor, and f_2 is the suppression factor.

$$\mathbf{f_1 = f_{shear} . f_{others}} \tag{2}$$

$$\mathbf{f_{shear}} = \frac{\delta_1}{\delta_2} \quad \text{where;} \tag{3}$$

δ_1 : Film thickness without interfacial shear stress

δ_2 : Film thickness with interfacial shear stress.

The interfacial shear stress is influenced by both the interface velocity and the mixture side velocity. Moreover, the entrainment from a liquid film is associated with the onset of disturbance waves at the interface and, in general, depends on both the vapor and the liquid flow rates. In fully turbulent flow, above a film Reynolds number of 3000 the condition for the onset of entrainment depend mainly upon the vapor velocity [5]. For this reason, the f_{others} in Equation (2) is correlated as,

$$\mathbf{f_{others} = 1 + C_1 . Re_L^{z1} + C_2 . Re_M^{z2}} \tag{4}$$

The build up of NC gases at the interface and its back diffusion into the core constitute a primary problem. The accumulation of NC gas at the interface is the principle reason for the mass diffusion resistance in radial direction, which causes lower condensation rates. This effect is encompassed into the correlations with the aid of air mass fraction in UCB correlation. However, air mass fraction is not defining the ongoing process, which is originally governed by concentration gradient formed between the interface and the core. Therefore, the Sherwood number is used instead of air mass fraction in the suppression factor, f_2. When the variation of f_2 is investigated with the Sherwood number, the segregation of individual runs from each other is observed and this situation is attributed to inlet pressure which is, therefore, superimposed into the correlation as air mole fraction. Under the light of these arrangements, the suppression factor is formulated as follows.

$$\mathbf{f_2 = 1 - C_3 . Shrr^{z3}} \tag{5}$$

where

$$\mathbf{Shrr = y_g . Sh} \tag{6}$$

y_g: Mole Fraction of air
Sh: Sherwood Number
C_1-C_3 and z_1-z_3 are the constants to be determined.
Results and the comparison of the correlations are given in section 4.2.

4. RESULTS

4.1. Experimental results

The heat flux distribution for experimental runs corresponding to the nominal system pressure, P_n, of 2, 3, and 4 bars, and including pure vapor and different mixture of air and vapor, are presented in Fig. 2, 3, and 4 respectively [4,6].

An increase in system pressure increases local heat flux and this can be attributed to the increase in wall subcooling degree that enhances the thermal driving force for heat transfer. Moreover, higher system pressure associated with the higher inlet temperature leads to a greater number of molecular collisions helping in the diffusive transport of energy. However, in our experimental investigation, the dependency of the wall subcooling degree, either measured (T_c–T_w) or predicted from Gibbs-Dalton Law (T_s–T_w), on system pressure is such that the wall subcooling degree remains nearly the same for the same inlet air mass fraction and for the different system pressure. This implies that the vapor mass flow rate may dominate over system pressure, concerning the effect on local heat flux, for cases with air/vapor mixture (Fig. 5). The situation is rather different in pure vapor runs, that is increase in system pressure has a strong effect on enhancement of predicted, and even measured, wall subcooling degree and hence on increase of local heat flux (Fig. 6).

4.2. Results of correlations

Using UCB condensation data base [7] for both pure and steam/air mixture available, the unknown parameters of the correlations have been estimated by using Marquardt-Levenberg non-linear parameter estimation method [8] which provides quicker convergence than alternative methods. Results of present correlations are given in Table I.

5. TAEA ACTIVITIES ON OECD/NEA ISP-42

TAEA participated to the OECD/NEA International Standard Problem No:42 (ISP-42) which is hosted by the Paul Scherrer Institut (PSI), Switzerland. The ISP-42 test was performed in the PANDA test facility, at the PSI, as a sequence of Phases A through F, representing typical passive safety system operating modes covering certain specific phenomena. The configuration used for ISP-42 was corresponding to the European Simplified Boiling Water Reactor containment and passive decay heat removal system at about 1:40 volumetric and power scale, and full scale for time and thermodynamic state.

** Mean Deviation$=\frac{1}{n}\sum_{1}^{n}\text{abs}\left[\frac{(h_{cal}-h_{exp})100}{h_{exp}}\right]$

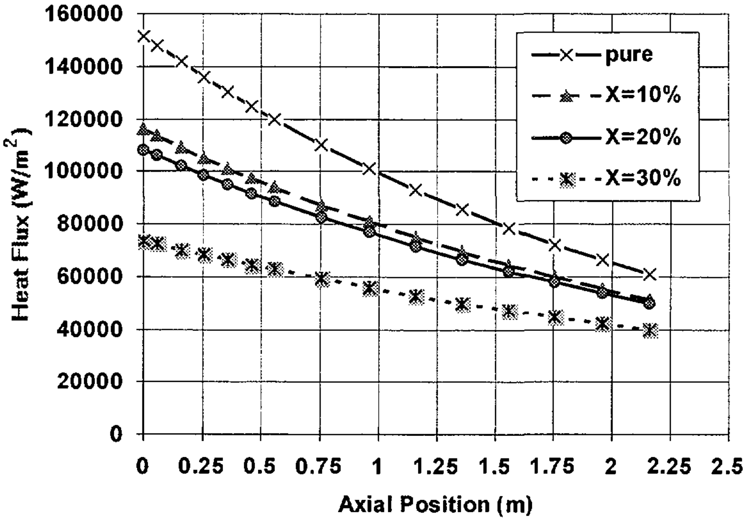

FIG. 2. Heat flux distribution along the condenser tube (P_n=2 bar, Re_v=54000–63000) [6].

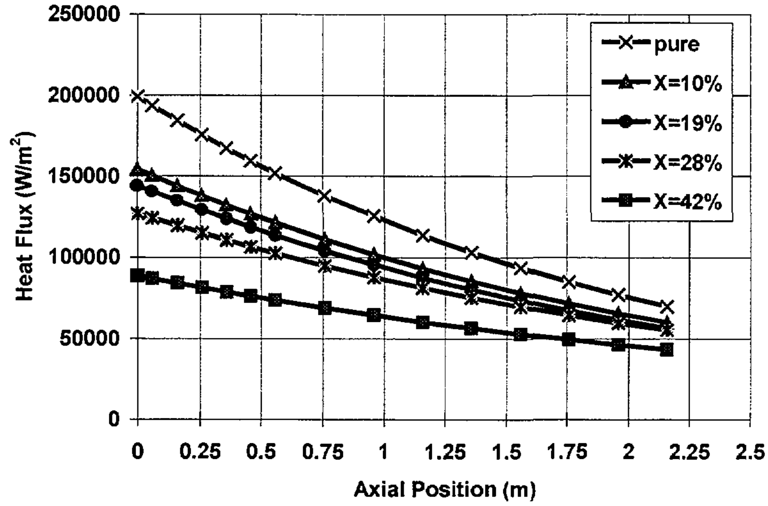

FIG. 3. Heat flux distribution along the condenser tube (P_n=3 bars, Re_v=67000–78000 and Re_v= 54000 for X_i=42%) [4].

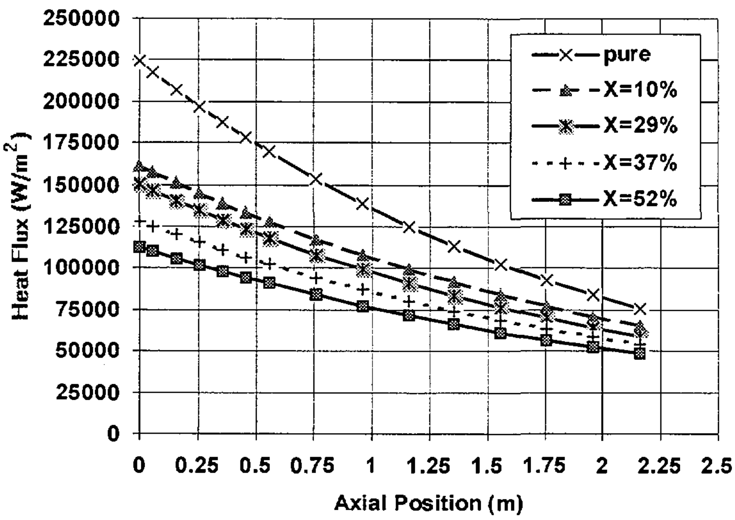

FIG. 4. Heat flux distribution along the condenser tube (P_n=4 bar, Re_v=77000–86000 and Re_v = 45000 for X_i=52 %) [4].

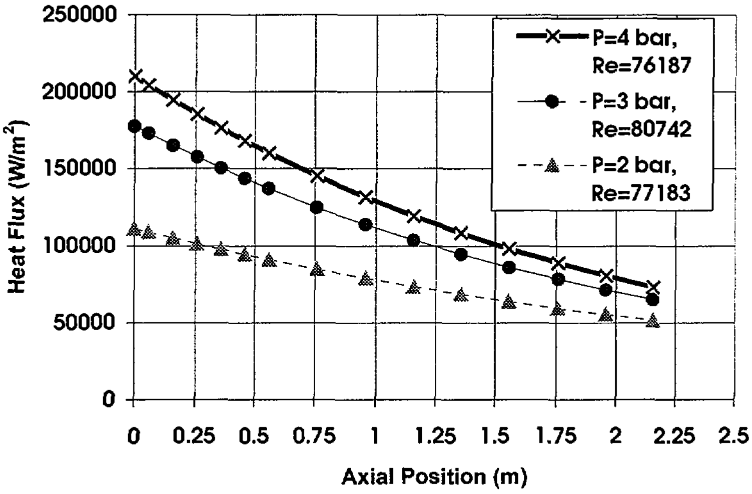

FIG. 5. Effect of system pressure (air/steam mixture; X_i=20 %) [4].

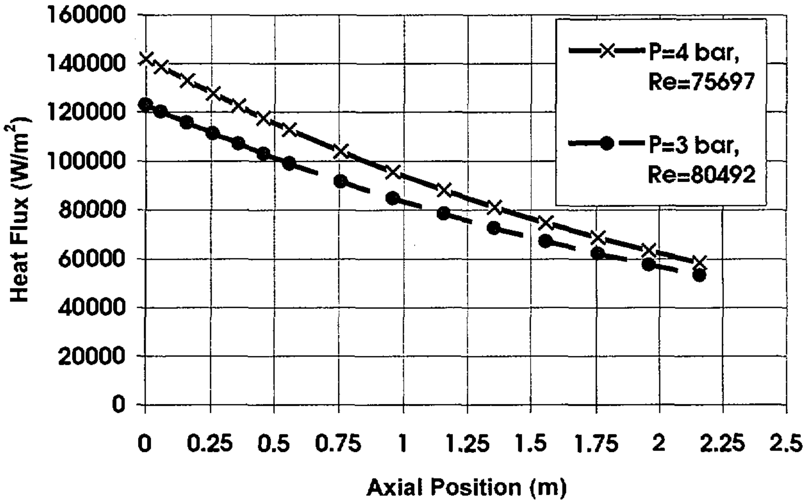

FIG. 6. Effect of system pressure (pure steam) [4].

TABLE I. COMPARISON OF CORRELATIONS

PURE STEAM	Mean Deviation**, %		
	f_{exp}>1.4		f_{exp}< 1.4
Present Study	5.26		7.18
UCB	10.57		
STEAM+NC GAS Based on X_g	Mean Deviation, %		
	X_g<0.1		X_g>0.1
Present Study	10.23		18.39
UCB	12.41		20.58
STEAM+NC GAS Based on Sh Number	Mean Deviation, %		
	Shrr<5	5<Shrr<25	Shrr>25
Present Study	17.22	16.17	9.16

Both the experimental results and prediction of the RELAP5/mod3.2.2 code reveals the fact that the system behaviour during Phase-A is highly affected by the performance of Passive Containment Cooling System (PCCS) heat exchangers. The objective of Phase-A is to investigate the start-up of passive cooling system when steam is injected into a cold vessel (dry-well) filled with air and to observe the resulting gas mixing and associated system behaviour. This simulation demonstrates the importance of both pure steam condensation and steam condensation in the presence of air for natural circulation in the system which in turn governs the realistic system behaviour. The system transient has been developed into two distinct parts: first, system heat-up and pressurization period (~3800 s) due to evaporation in the reactor pressure vessel with constant heat input from the heaters in the core and weak heat removal rate from PCC heat exchangers as the result of high air mass fraction; second, system pressure stabilization period (from 3800 s to the end of analysis) during which PCC heat exchangers become active as the result of venting of air from PCC tubes. The results of RELAP5 predictions for PCC-1 heat exchanger are presented in Figs. 7 and 8 for time 1500 s and 5000 s, respectively. These two distinct times are selected to demonstrate the PCC heat exchanger performance during aforementioned two distinct parts of the transient. In these figures, only the results of 5 tubes (out of 20 tubes) which were lumped to single pipe consisting of 10 control volumes were shown. Two parameters are essential with respect to PCC heat exchanger performance; local heat flux and air mass fraction. As given in Section 4.1, the system pressure is also an important parameter for the rate of condensation. However, the effect of the system pressure is expected to be small in these two figures since the pressure difference is small, i.e. 0.7 bar.

As could be seen in these figures, the local heat flux is affected by the presence of air inside the PCC heat exchanger tubes, as expected. Since the local air mass fraction is about 0.94 (almost pure air) and constant throughout the length of the condenser tubes as predicted at t=1500 s (Fig. 7), the local heat flux values are suppressed to about 0.2 % of the local heat flux values predicted at t=5000 s during which condenser tubes are full of almost pure steam down to 1.3 m (about ¾ of total length). The maximum air mass fraction at the bottom of the condenser tubes is less than 0.3 at 5000 s. It is to be noted that some amount of air is accumulated in bottom part of tubes and lower drum of PCC-1 after 3800 s due to terminated vent flow from PCC lower drum to the wet-well tanks. The accumulation of air at the bottom of tubes shorten the active condensation length to about ¾ of total lenght, as seen in Fig. 8, and this reveals the fact that percent of shortening of active condensation length is also the function of system pressure and differential pressure developed between PCC lower drum and wet-well tanks. In other words, system pressure and differential pressures developed between components in a system operating under natural circulation could highly affect the rate of vent of air from PCC tubes and in turn the effective condensation length.

6. CONCLUSIONS

In this paper, activities of the TAEA concerning condensation in the presence of NC gas were given. In the experimental analysis, it was observed that the overall agreement between the analytical analysis and the experimental data obtained for heat flux or heat transfer coefficients is reasonably good. For example, the heat flux significantly decreases as the inlet air mass fraction increases. Moreover, it could be promulgated that the effect of superheating of inlet stream possesses no considerable effect on the heat flux. Another conclusion emerging from experimental studies is that the local heat flux values for pure steam and mixture runs come closer towards the bottom of the condenser tube.

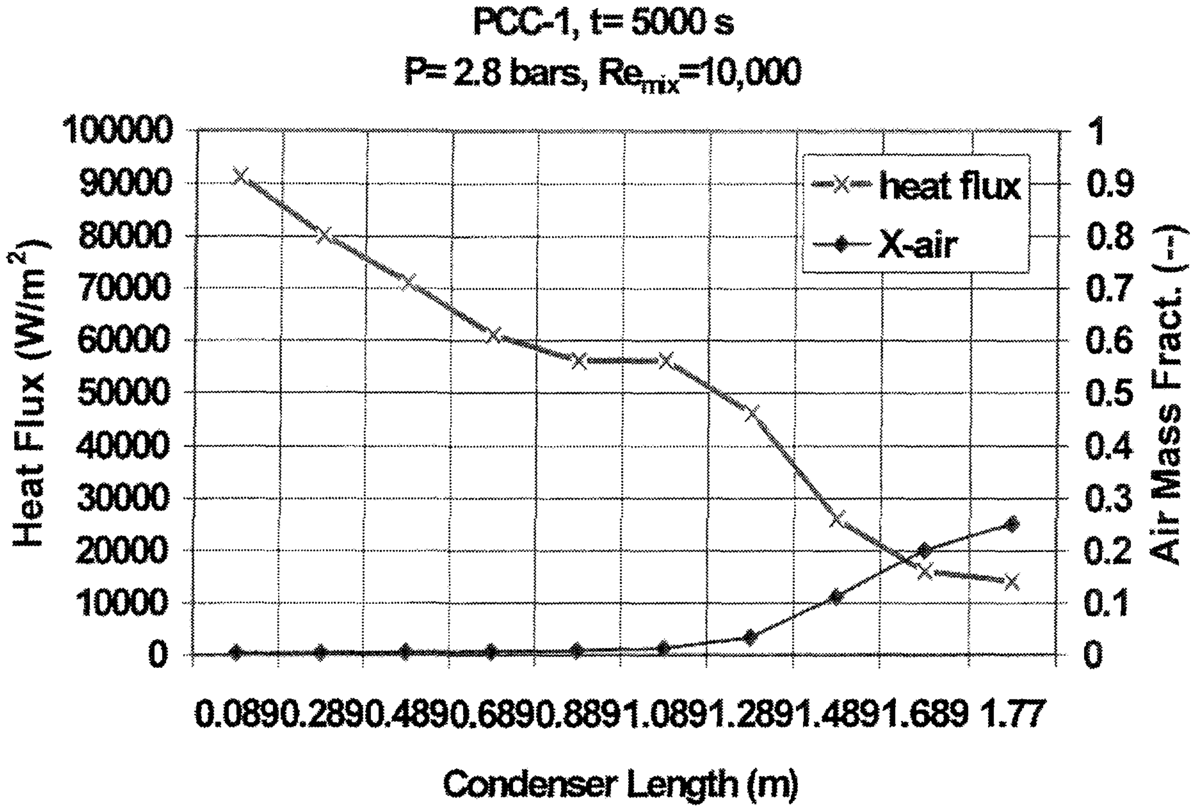

Fig. 7. Local heat flux and air mass fraction distribution along the axis of the PCC-1 for t= 1500 s.

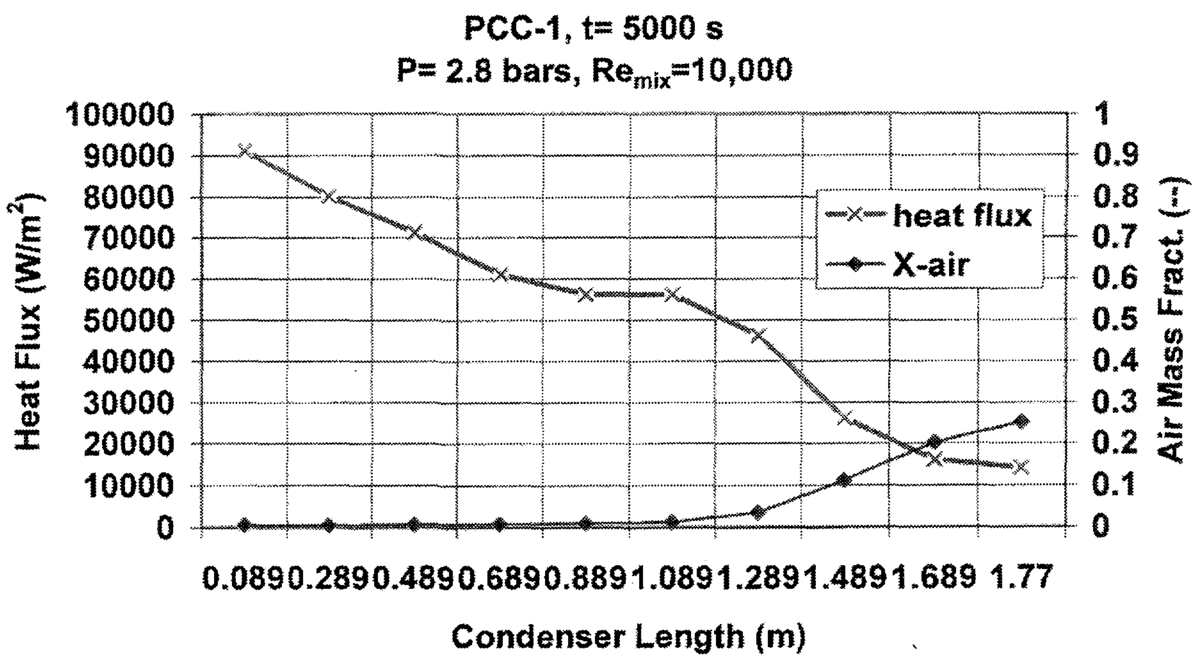

Fig. 8. Local heat flux and air mass fraction distribution along the axis of the PCC-1 for t= 5000 s.

The correlations obtained from UCB database show that the mixture side Reynolds number is also a strong parameter affecting heat transfer coefficient. However, it should be noted that the given correlations stay behind the real phenomenon occurring inside the tube. Because, neither interfacial waviness nor the suction effect is taken into account. At the same time, these correlations depend on the flow regimes of either phase. If turbulent- turbulent flow regime is in question, these correlations fail. Therefore, the studies have been concentrated on an analytical solution in which a film-wise condensation of a down-flow steam/NC gas mixture in a vertical tube is considered. In this analytical model, the mixture side is treated as turbulent flow. The effect of Prandtl number, interfacial shear stress, interfacial waviness, entrainment and deposition and especially the suction have been covered in our model. The two-fluid formulation constitutes the main routine. The interfacial temperature is estimated using the stagnant film theory. Moreover, for the mixture side, the turbulence model is developed in order to elaborate suction effect, which is one of the primary reasons of the enhancement of the mixture side heat transfer coefficient. Finally, it should be stated that the diffusion layer theory is superimposed into the model to define the closure relations.

The condensation is an important heat transfer mode for natural circulation in innovative systems nuclear reactor systems like the Simplified Boiling Water Reactor design. The realistic prediction of local heat flux in heat exchangers of passive containment cooling system is essential and due to this reason physical models in computer codes for condensation and effect of NC gases on condensation should be assessed. Though very preliminary, ISP-42 study on PANDA reveals us the fact that the realistic prediction of the performance and behaviour of PCC heat exchangers could affect the overall system behaviour and the rate of condensation heat transfer is the function of air mass fraction at the inlet of condenser tubes and effective condensation length.

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