ACTIVITIES ON CONDENSATION IN THE PRESENCE OF AIR AND SIMULATIONS OF INNOVATIVE NUCLEAR POWER PLANT DESIGN

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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 minimized 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), utilizes 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.

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 [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. 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=2-6 bars, Re_v= 45,000-94,000, and X_i=0 %-52 %

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 is also clarified by the accumulation of the NC gas at the interface, 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

$$\mathbf{f = f_1 . f_2} \tag{3.1}$$

where

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

$$\mathbf{f_1 = f_{shear} . f_{others}} \tag{3.2}$$

$$\mathbf{f_{shear} = \frac{\delta_1}{\delta_2}} \quad \text{where;} \tag{3.3}$$

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 (3.2) is correlated as,

$$\mathbf{f_{others} = 1 + C_1 . Re_L^{z1} + C_2 . Re_M^{z2}} \tag{3.4}$$

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 f_2 vs. Sherwood number is depicted, the segregation of individual runs from each other is observed and this situation is attributed to inlet pressure which is superimposed into the correlation as air mole fraction. Under the light of these arrangements, the suppression factor is formulated as follows.

$$\mathbf{f_2 = 1 - C_3 . Shrr^{z3}} \tag{3.5}$$

where

$$\mathbf{Shrr = y_g . Sh} \tag{3.6}$$

y_g: Mole Fraction of air

Sh: Sherwood Number

C_1-C_3 and z_1-z_3 are the constants to be determined.

EXPERIMENTAL RESULTS

The heat flux distribution for experimental runs corresponding to the nominal system pressure, P_n, of 2 and 4 bars, and including pure vapor and different mixture of air and vapor, are presented in Fig. 4.1 and 4.2, respectively [4, 6]. It is clear in these figures that the heat flux drastically decreases as inlet air mass fraction increases. This situation is the evidence for how some amount of air, mixed with vapor, degrades the performance of the heat exchanger. The decrease of local heat flux at the middle of the test section (~1 m from the top) as compared to the corresponding pure vapor case is summarized as:

- P_n=2 bars: 20 % (X_i=10 %), 24 % (X_i=20 %), 45 % (X_i=30 %)
- P_n=4 bars: 22 % (X_i=10 %), 24 % (X_i=20 %), 28 % (X_i=29 %), 37 % (X_i=37 %) 44 % (X_i=52 %)

Another point to be emphasized is that local heat flux values for pure steam and air/steam mixture runs get closer towards the bottom of the condenser tube due to diminishing condensation rate as the result of increased resistance of condensate film. This means that condensate film resistance in pure steam runs tends to dominate over diffusion resistance in air/steam mixture runs, at the bottom of the condenser tube.

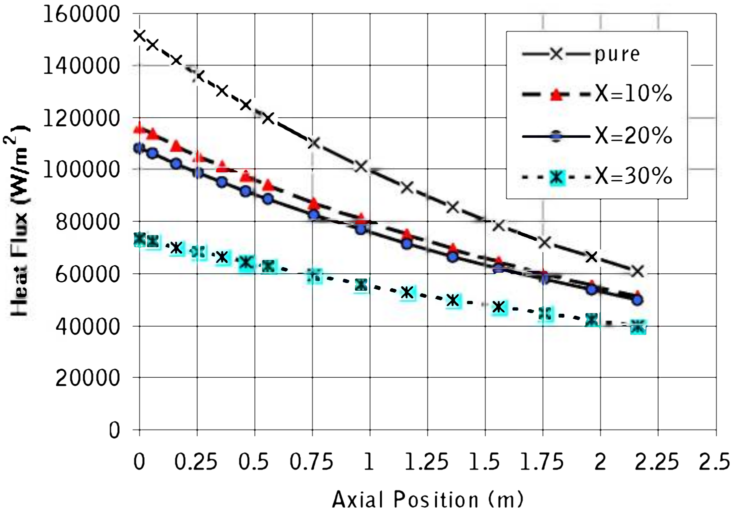

Fig. 4.1. Heat Flux Distribution along the Condenser Tube

(P_n=2 bars, Re_v=54000–63000)

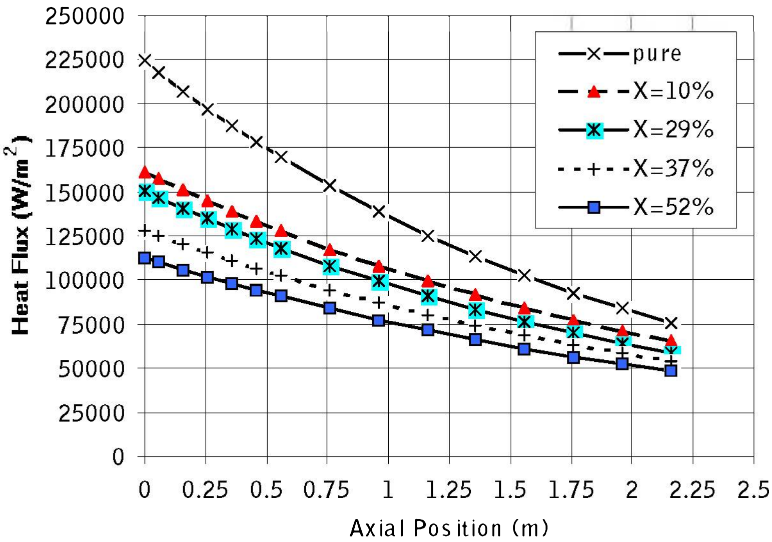

Fig. 4.2. Heat Flux Distribution along the Condenser Tube

(P_n=4 bars, Re_v=77000–86000 and Re_v=45000 for X_i=52 %)

TAEA ACTIVITIES ON OECD/NEA ISP-42

The Turkish Atomic Energy Authority (TAEA) participated to the OECD/NEA International Standard Problem No:42 (ISP-42) which is hosted by the Paul Scherrer Institut (PSI), Switzerland. 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.

Both the experimental results and prediction of the RELAP5/mod3.2.2 code reveals the fact that the system behavior 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 behavior. 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. 5.1 and 5.2 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. Two parameters are essential with respect to PCC heat exchanger performance; local heat flux and air mass fraction.

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. 5.1), 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 length, as seen in Fig. 5.2, 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.

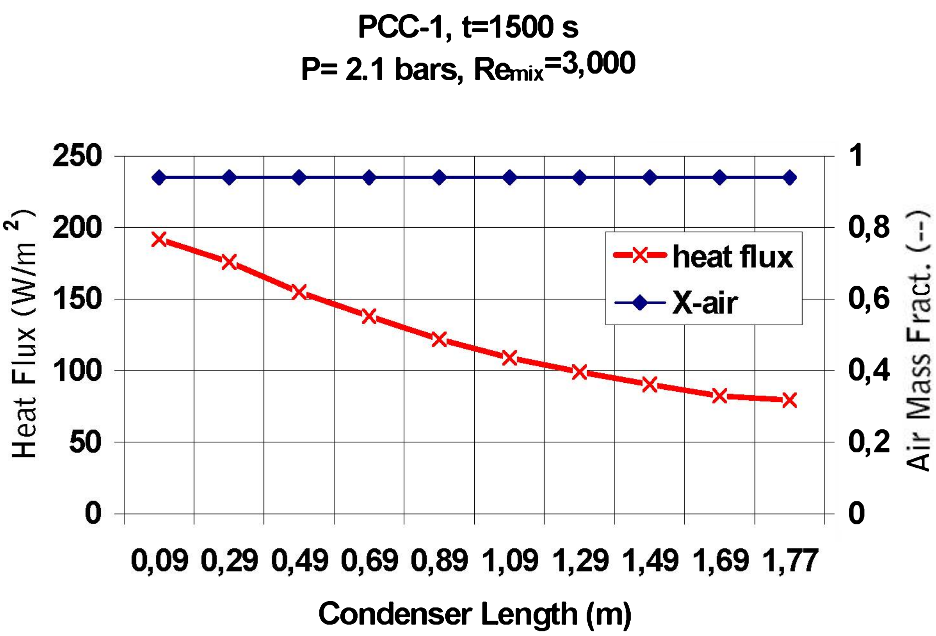

Fig. 5.1. Local Heat Flux and Air Mass Fraction Distribution along the Axis of the PCC-1 for t= 1500 s

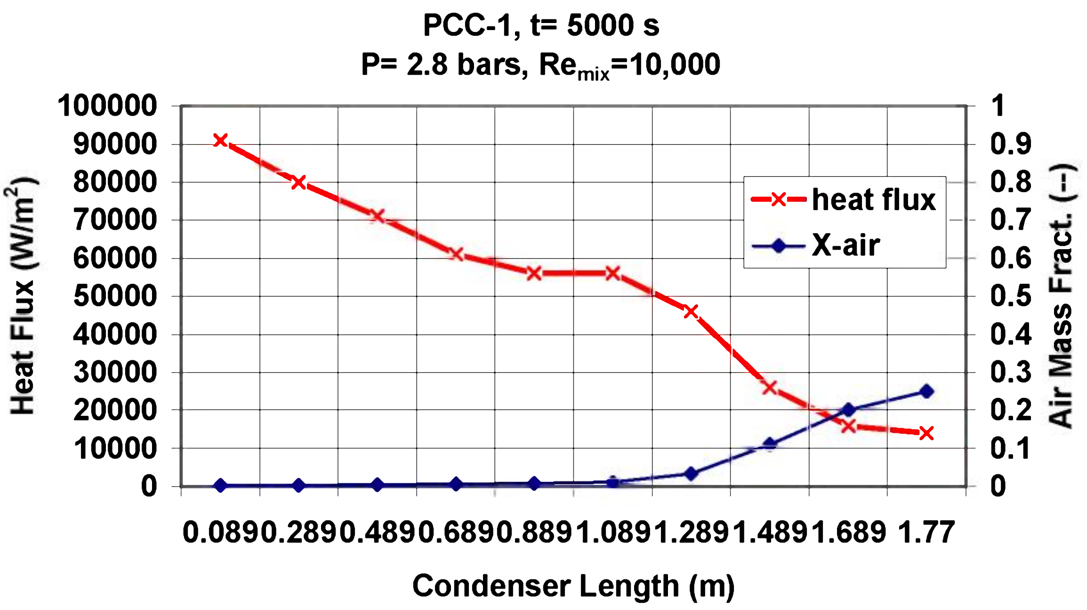

Fig. 5.2. Local Heat Flux and Air Mass Fraction Distribution along the Axis of the PCC-1 for t= 5000 s

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 possess 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. 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

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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