THE RESEARCH ACTIVITIES ON IN-TUBE CONDENSATION IN THE PRESENCE OF NONCONDENSABLES FOR PASSIVE COOLING APPLICATIONS

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Abstract

The introduction of nuclear power becomes an attractive solution to the problem of increasing demand for electricity power capacity in Turkey. Thus, Turkey is willing to follow the technological development trends in advanced reactor systems and to participate in joint research studies. 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 a validation program is also important for the assessment of advanced computer codes which are currently used for design and licensing procedures. The condensation mode of heat transfer plays an important role for the passive heat removal applications in the current nuclear power plants (e.g. decay heat removal via steam generators in case of loss of heat removal system) and advanced water-cooled reactor systems. But it is well established that the presence of noncondensable gases can greatly inhibit the condensation process due to the build-up of noncondensable 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 noncondensable. This paper describes the research activities at the Turkish Atomic Energy Authority concerning condensation in the presence of air, as a noncondensable gas.

1. INTRODUCTION

A part of our long term research and development efforts in Turkey is planned to concentrate on passive systems and advanced fuels. The research on passive systems mainly comprises the computer code assessment studies and includes the applications for both old and new generation reactor systems. The research work concerning the application of condensation in the presence of air, as a noncondensable gas, was first undertaken for a Once Through Steam Generator (OTSG) type of PWR, for which, experimental data were available. These experimental data were obtained from the 2x4 test loop of University of Maryland at College Park (UMCP) and addressing a very important safety issue so called the loss of residual heat removal system after reactor shutdown. The experimental data were used for the assessment of RELAP5 computer code and both the effect of Nusselt model, incorporated in the code as the condensation model, and the effect of nodalization were investigated. But the lacking of measurements for the inside of SG has led us to the conclusion that the separate effect test is strongly needed for the investigation of in-tube condensation and the effect of noncondensables on the condensation mode of heat transfer. Thus, an experimental study, which will enable us for the fundamental investigation of condensation in the presence of air, was planned in corporation with the Department of Mechanical Engineering of the Middle East Technical University (METU), Ankara, in the frame of a project between the Turkish Atomic Energy Authority (TAEA) and METU. The project is now in the design stage of the separate effect test facility. The planned experimental investigations will cover a wide range of mixture flow rate, i.e. nearly stagnant steam-air mixture flow and forced convection condensation, with respect to different pressure and air mass fraction values.

2. THEORETICAL BASIS

The Nusselt laminar film condensation model [1] is widely used in system analysis codes, such as RELAP5 and TRAC, and considered as a base model for our investigations. The model needs to be improved since the analytical derivation of the model is valid for situations where the steam is basically stagnant. In cases where the steam flows past cold surface, the model will predict the heat transfer rate that is significantly too low. However, one of the basic assumptions of the analytical derivation of Nusselt, that is, linear temperature distribution exists between wall and vapor conditions, can be considered reasonable in forced convection conditions since the resistance of the condensate film is further diminished because of the thinning, rippling and waviness. But since the influence of turbulence, due to waviness and rippling, is not incorporated in the Nusselt model McAdams suggested to increase the heat transfer coefficient by 20% [2].

The application of Nusselt model, incorporated in advanced computer codes, is another problematic area since the nodalization scheme can highly affect the results. The volume length (L) selected is the input for the average heat transfer coefficient ($h \propto (1/L)^{0.25}$) and it should, preferably, be the length of effective condensation. Problems may be encountered when fine nodalization model is applied since the logic behind the derivation of the model originally assumes the film re-development in each volume where the condensation prevails. But, instead, the film thickness will increase continuously in downward direction, irrespective to the nodal model selected. Thus, the model as coded in computer programs can be expected to overpredict the heat transfer coefficient when the condensation length is discritized by fine mesh model.

As mentioned above, the condensate film provides the only heat transfer resistance in case of pure vapor condensation whereas the main resistance lies in the gas/vapor boundary layer if small amounts of a noncondensable gas are also present. Minkowycz and Sparrow reported a 50% or more reduction of heat transfer rate due to an air mass fraction as low as 0.5% [3]. Many experimental investigations reveal the fact that the diffusional resistance is the dominant factor for the reduction in heat transfer in the presence of a noncondensable gas. From the computational point of view, the presence of noncondensable gas urges us to use fine node models for better axial gas mass fraction distribution which then results in above explained drawback in predicting the local heat transfer coefficient.

Traditionally the reduction factor, which is the function of partial pressure of steam in RELAP5 [4], has been used for reducing the heat transfer coefficient. This approach needs to be improved since degradation of the heat transfer coefficient strongly depends on this factor. Some recent experimental investigations have shown that the diffusive mass transfer resistance in the gas/steam boundary layer, through which the heat transfer consists of the sensible heat transfer and the latent heat given up by the condensing vapor, controls the heat transfer mechanism, that is, the presence of the noncondensable gas is the actual cause of the existence of temperature and concentration gradients. The theoretical approach of the experimental investigation (performed by using a vertical tube with 46.0-mm-i.d.), undertaken at Massachusetts Institute of Technology (MIT), Cambridge, have revealed that the general form of the local Nusselt number is the function of Reynolds (mixture), Schmidt, Jacob nondimensional number groups, and gas mass fraction [5]. The comparable work available on this subject is that of Vierow and Schrock at the University of California Berkeley (UCB), and the correlation obtained for the local heat transfer coefficient is the function of the heat transfer coefficient for pure steam condensation based on Nusselt model, condensate film Reynolds number and air mass fraction. The experiment, performed at the UCB, was made using a 22.0-mm-i.d. vertical tube, natural circulation air-steam system [5].

3. RELAP5 SIMULATIONS

The RELAP5 simulations comprise the major part of the work undertaken for the investigation of condensation in the presence of noncondensable. These simulations are aimed to study the capability of the code to capture the phenomena observed in the experiments. For this purpose, our investigations are based on two experimental data sets, that are, the data from UMCP integral test facility and MIT separate effect test facility. Apart from the simulations of test facilities, a parametric study for the Inherently Safe Boiling Water Reactor (ISBWR) is also carried out.

3.1 THE SIMULATION OF THE UMCP INTEGRAL TEST FACILITY

The operational characteristics of the test facility during the experiment, performed for the simulation of loss of residual heat removal system after reactor shutdown, may be considered to be different than those of the passive safety systems of new generation reactor types. This simulation leads us to understand the major role of the condensation phenomenon for heat removal performance and the effect of condensation on primary loop parameters. The simulation capability of RELAP5 is also assessed against the experimental data.

The integral test facility is installed at, and operated by, the University of Maryland, and is a 1/500 scaled model of a Babcock and Wilcox PWR with two loops [6]. The heat addition into the loop is accomplished by means of 15 heater rods of 2.54 cm diameter and 0.6096 m active length. The two steam generators are of Once-Through Steam Generator (OTSG) type and made of 28 tubes. The tubes are 3.905 m long and have an inside diameter of 29.97 mm and an outside diameter of 31.75 mm.

The experiment is initialized at cold conditions, i.e. the system is under atmospheric condition, temperature is 30 °C, and primary loop is drained down to pressurizer surge line connection. The hot steady-state condition is reached by the establishment of Boiler-Condenser Mode (BCM) and general characteristics of this condition are: system pressure is 440 kPa, upper parts of vessel and hot-leg are at saturation temperature (~145 °C), and SG primary level is 75%. The thermal power during BCM is 34.9 kW and heat removal via SG is mainly by means of condensation. The UMCP test facility is simulated by RELAP5 [7] and the role of condensation and the inhibiting effect of air on condensation process, as predicted by RELAP5, is given in Fig. 1 and the primary system pressure at the BCM predicted by RELAP5 code is as close as 5.5% compared to the experimental data (Fig. 2). It is to be noted that air is accumulated above the water level in the SG and the major part of heat transfer by condensation takes place in the uppermost volume.

3.2 THE SIMULATION OF THE MIT TEST FACILITY

The experimental apparatus [5] consists of an open cooling water circuit and an open noncondensable gas/steam loop. The main components of the gas/steam part of the facility are the boiler vessel (4.5 m height, 0.45 m inside diameter) and cooled vertical test section, that is, the condenser tube. The tube is 2.54 m long (effective) and has an outside diameter of 50.8 mm and an inside diameter of 46.0 mm. The condenser tube is surrounded by a jacket pipe (62.7 mm inside diameter).

Experiments are performed for air-steam mixture inlet temperatures of 100, 120, and 140 °C. At each inlet temperature setting, the steam flow rate is varied by using different boiler power levels (6, 13, and 20 kW). The inlet air mass fraction is varied from 10 to 35% for each

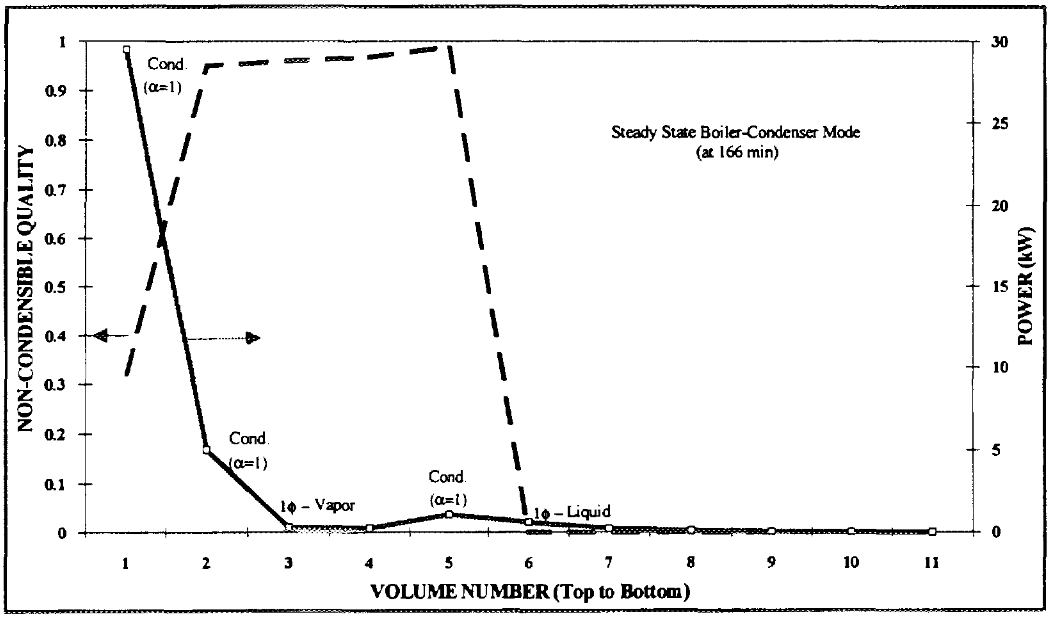

Figure 1. Heat Transfer Characteristics of UMCP Steam Generator at the BCM

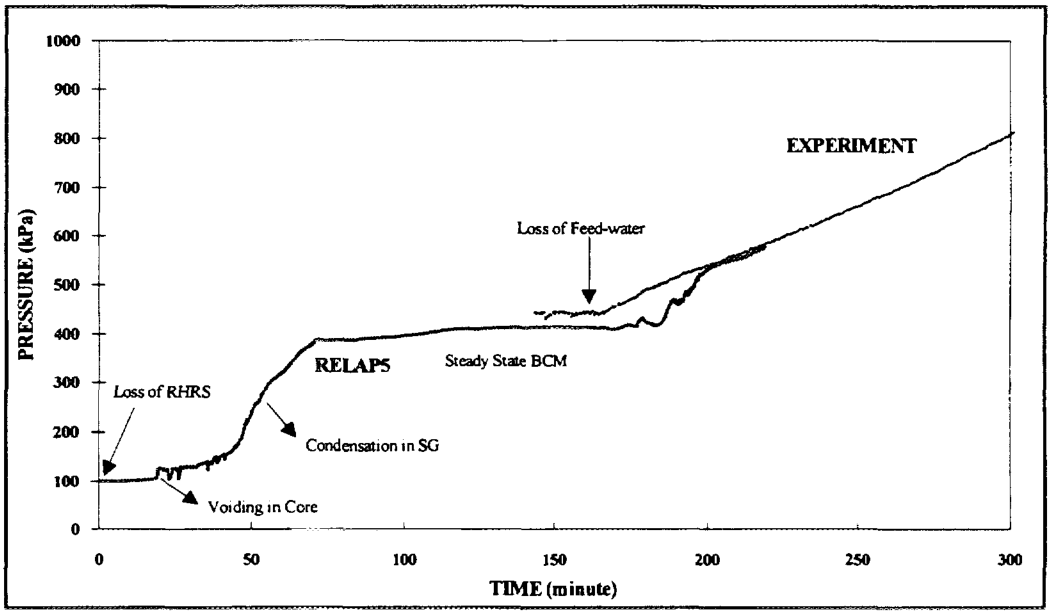

Figure 2. System Pressure of UMCP Test Facility during Loss of Residual Heat Removal System and Loss of Feed Water System Accidents

inlet temperature and power level setting. A similar test matrix is formed for helium-steam mixture, that is, for different mixture inlet temperatures (100, 120, and 140 °C) the steam flow rate is varied by using 6 and 13 kW power settings. The inlet helium mass fraction is varied from 2 to 10% [5].

The main objective of the experimental investigations, performed at MIT, is to measure local heat transfer coefficients for steam condensing in the presence of air or helium inside a tube. Moreover, this study aims to represent the operating characteristics of the Isolation Condenser (IC) which is the main component of the Passive Containment Cooling System (PCCS) of Simplified Boiling Water Reactor (SBWR) design.

A RELAP5 model of MIT test facility is prepared (Fig 3) and RELAP5 results, obtained for different cases in the test matrix, are compared to the experimental data. Since there are few forced convection in-tube condensation studies in open literature and most of them can not represent the operating characteristics of the IC, the MIT data could enable us to extend our simulation capabilities to the passive safety systems of advanced reactor designs.

Two typical RELAP5 results are compared with the experimental data in Figs. 4 and 5. The parameters selected, for the comparison, are the heat transfer coefficient and the air mass fraction with respect to the channel length. The case is characterized by the operating conditions, namely, the inlet mixture temperature is 120 °C and the inlet air mass fraction is 0.08. For fixed inlet conditions, the heat transfer coefficient decreases by the accumulation of air. The RELAP5 prediction for air mass fraction follows the trend of experiment very closely (especially at the entrance region) while the prediction for heat transfer coefficient yields an overestimation compared to the experimental data. But it is interesting to note that the heat transfer coefficient calculated for the uppermost volume is very close to the experimental data. Another important parameter to be considered is the effective condensation length which is the function of axial air mass distribution. The effective condensation length, for the case presented in Figs. 4 and 5, is overpredicted by the code.

3.3 THE SIMULATION OF THE INHERENTLY SAFE BOILING WATER REACTOR CONCEPT

The Inherently Safe Boiling Water Reactor (ISBWR) concept is a 340 MWe (1000 MWt), natural circulation, indirect cycle small boiling water reactor [8,9]. The design features a multi-cavity Prestressed Concrete Reactor Vessel (PCRV) which contains all primary loop components (i.e. reactor, steam separator, subcooler/preheater, condenser/evaporator). Fig. 6 shows a section view of the ISBWR. Under normal operation, the naturally circulated primary fluid rises vertically in chimney after exiting from the core and enters the steam separator. The separated steam in the steam separator rises through in chimney cavity and then goes through the steam by-pass orifice to the upper section of downcomer cavity where the Condenser/Evaporator (C/E) is located. The saturated water goes through the water by-pass orifice to the lower section of the downcomer cavity where the Subcooler/Preheater (S/P) is located. The secondary loop coolant flows in the S/P tubes and is heated up, and then goes to the C/E tubes and is evaporated. The ISBWR is inherently safe against any primary breaks. However, any kind of secondary fault (e.g. feed water pump trip, rupture of one of the S/P or C/E tubes) may lead to loss of heat sink. In that case, the steam driven jet injector uses the decay heat steam to pump water from suppression pool to cool the reactor core.

The primary loop operation characteristics are function of the secondary loop pressure, inlet temperature, and mass flow rate. Condensation without noncondensable occurs on the main steam generator tubes which is not a part of safety system of ISBWR. In the ISBWR, the condensation on the C/E tube outside surface plays main role for the system steady-state operation parameters.

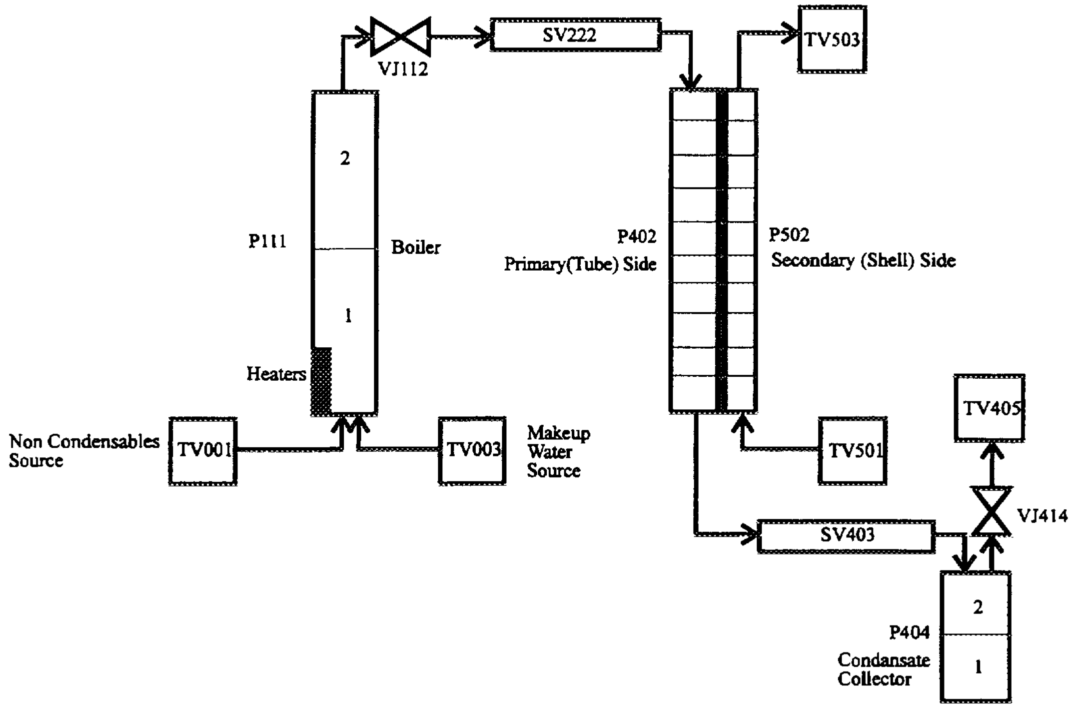

Figure 3. RELAP5/MOD3 Nodalization for MIT In-tube Condensation Experiment Setup

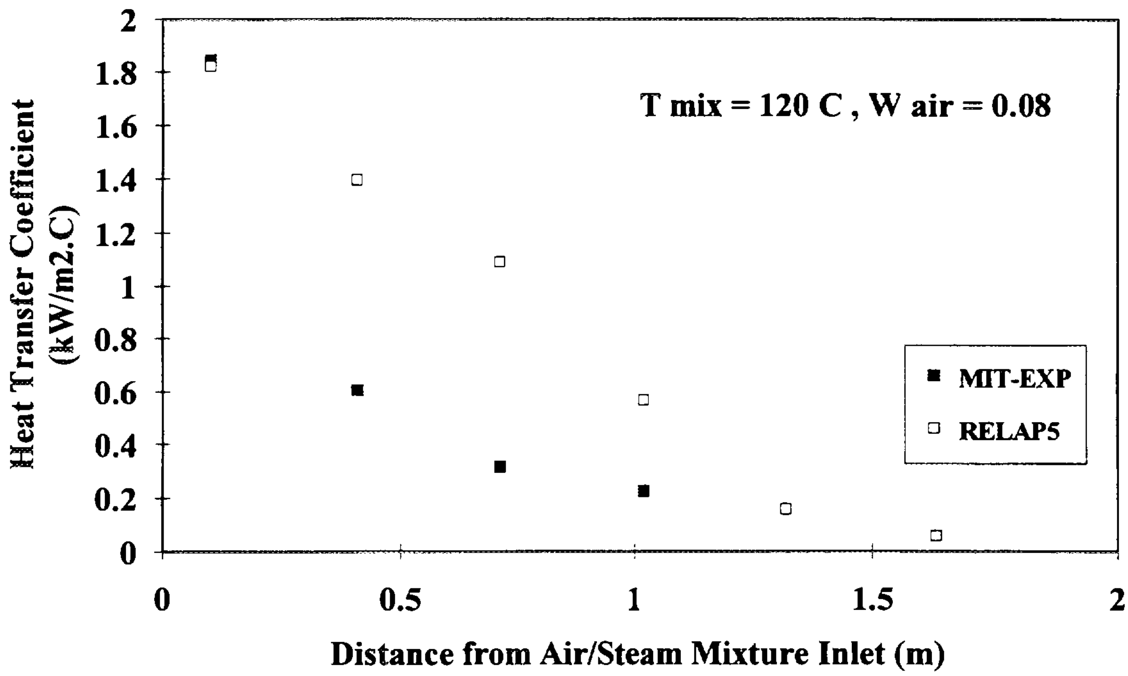

Figure 4. Axial Variation of Heat Transfer Coefficient

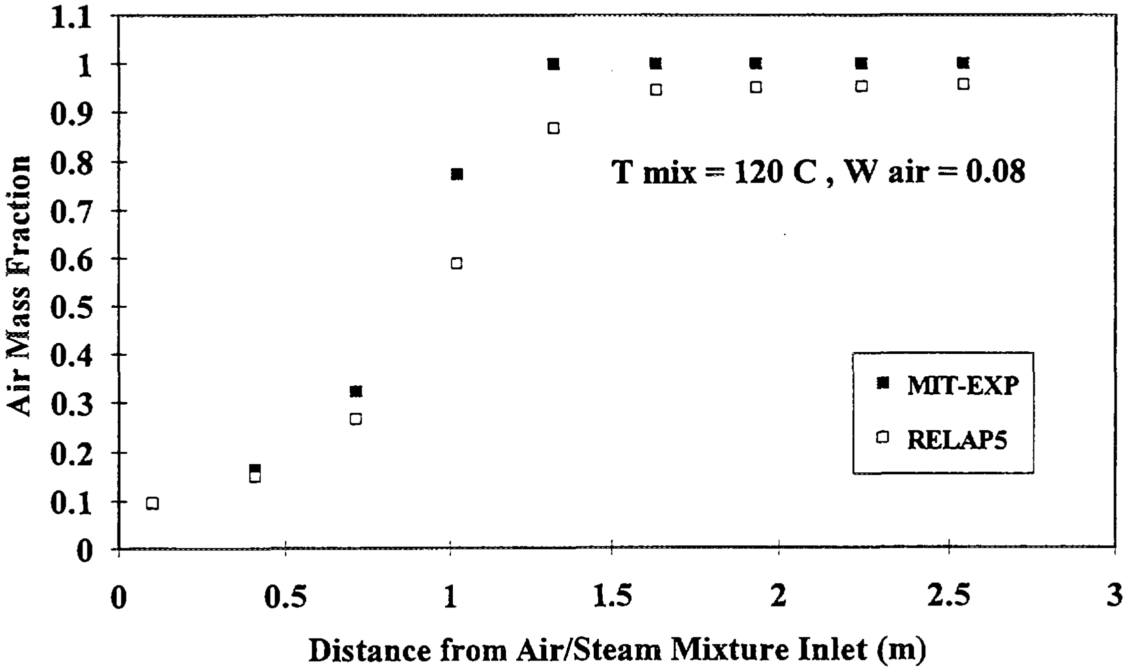

Figure 5. Axial Variation of Air Mass Fraction

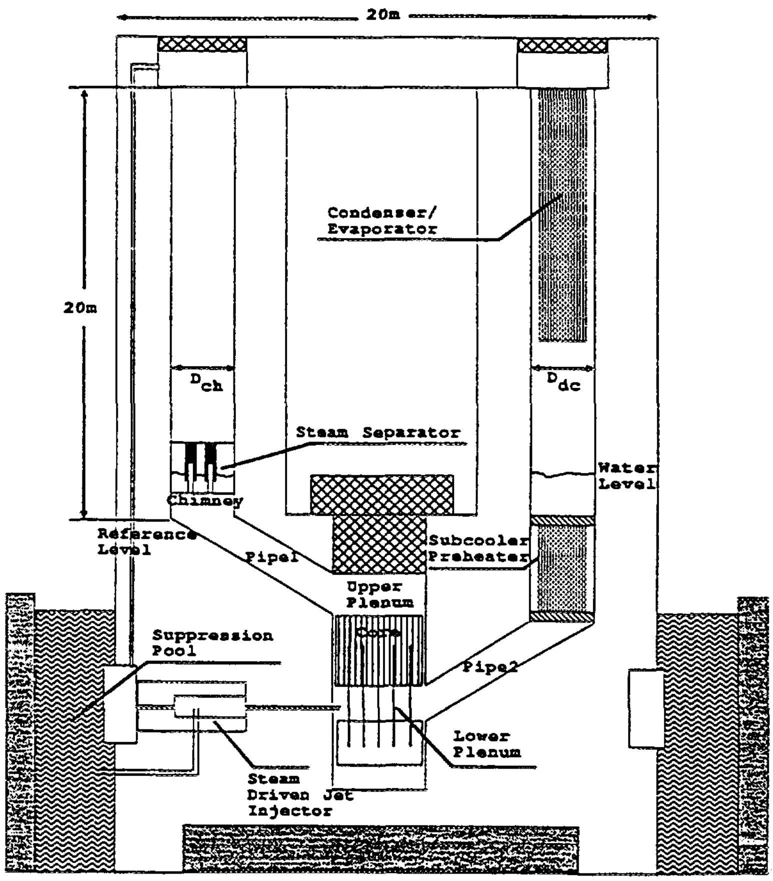

Figure 6. Section View of the Inherently Safe Boiling Water Reactor (ISBWR)

4. THE PROJECT RELATED TO THE EXPERIMENTAL INVESTIGATION OF IN-TUBE CONDENSATION IN THE PRESENCE OF AIR

The experimental data available for in-tube condensation in the presence of air are very limited and most of the experimental correlations developed are applicable for the particular system for which they were developed. It is also needed to assess the experimental data available in the open literature with some independent experimental measurements provided that the experimental conditions are similar.

An experimental program was planned in cooperation with the Department of Mechanical Engineering of the Middle East Technical University (METU), Ankara, for the investigation of in-tube condensation in the presence of air in the frame of a project between TAEA and METU. The project is now in the design stage of the facility.

The project aims to investigate the condensation phenomenon for two different cases. First, the case corresponding to the operating conditions of SG of UMCP test facility, i.e. the lowest part of the SG tube is full of water and some amount of air is accumulated just above the water level. In this case, only the vapor flows -with relatively low Reynolds number- from top of the SG tube and the water level is kept constant throughout the experiment. The mass of air accumulated above the water level can affect the effective condensation length. The second case planned is for forced convection condensation. The test matrix proposed for this case will comprise different system pressures (1-5 atm) with the variation of inlet air mass fraction for each pressure setting. The effect of mixture Reynolds number will also be considered. There are two condenser tubes, planned to be used for the experiments, with different inside/outside diameters (25.0/32.0 mm, 47.0/51.0 mm) and same total length (~2.0 m).

5. CONCLUSIONS

The annular film condensation of vapor inside vertical tubes is extremely important for applications concerning chemical and power industries. By the investigations regarding condensation in unconfined spaces it has been well established that the existence of noncondensable gases can greatly inhibit the condensation process, and in turn, the heat transfer performance of heat exchangers. Among such investigations there are also theoretical and experimental studies for plane surfaces, with different orientations, to simulate the cooling conditions of containment wall. But the experimental investigations addressing the research on in-tube condensation in the presence of noncondensable(s) for passive cooling applications of new generation reactors are very limited in the open literature.

The experimental and computational research activity for in-tube condensation in the presence of noncondensable(s) is planned and launched by TAEA to make contributions in the area of passive cooling applications. The mechanism beyond the effect of noncondensable gases for the degradation of heat transfer rates by the condensation process is rather complicated. Thus, the research program is also supported by the theoretical investigations.

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