8.1 Experimental Investigation of Thermal-Hydraulic Performance of PCCS with Horizontal Tube Heat Exchangers: Single U-Tube Test

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Abstract

JAERI and JAPC started a cooperative study to verify performance of a PCCS using horizontal heat exchanger for next-generation BWR in 1998. A test facility with a horizontal single U-tube was constructed in JAERI in 1999 to investigate fundamental condensation behavior under influences of non-condensable gas. Preliminary pre-test analyses were performed using RELAP5/ MOD3.2.1.2 code to expect the experimental outcomes by incorporating a correlation for condensation degradation because of non-condensable gas by Ueno et al. for better prediction. Preliminary results from both experiments (shakedown) and pre-test analyses indicated that the PCCS using horizontal U-tube heat exchanger is promising. Steam generated under assumed severe accident conditions; steam generation rate ≈ 1% core power, non-condensable gas concentration of 1% and simulated containment vessel pressure of 0.7 MPa, was totally condensed with a small differential pressure across inlet and outlet plenum. Experimental data will be accumulated to develop models and correlations for a better prediction of responses of the PCCS using horizontal heat exchanger during postulated severe accidents.

1. Introduction

A passive containment cooling system (PCCS)[1-7] is under planning to be used for a long-term cooling of primary containment vessel (PCV) of next-generation BWRs during a severe accident in case that residual heat removal (RHR) systems are in failure. The pressure of the PCV will be maintained as low as possible by condensing steam with no active components.[Δ] JAERI and JAPC have agreed and started to jointly study the availability of the PCCS using a horizontal U-tube heat exchanger in 1998.

Fundamental experiments using a horizontal single U-tube were started in August, 1999 in JAERI to study condensation heat transfer characteristics for steam/non-condensable gas mixture and flow behavior of condensate and non-condensable gas under postulated severe accident conditions. Parameter experiments are planned to perform changing tube geometry and flow conditions. The experimental results will be used to prepare correlations to predict steam condensation behavior under severe accident conditions by the aid of code analyses.

Preliminary pre-test analyses of the condensation heat transfer in the horizontal U-tube were performed using RELAP5/ MOD3.2.1.2 code to expect the experimental outcomes. A correlation to predict degradation of steam condensation by non-

[Δ] Non-condensable gases such as hydrogen and carbon-oxide are generated by the interaction of high-temperature corium with water and concrete of containment base mat, and oxidation of zirconium of core cladding, and will be stored in wetwell with nitrogen gas. The PCCS is not intended to mitigate the pressurization by such gas generation.

condensable gas was incorporated into the code.

This paper summarizes such current experimental and analytical efforts to clarify the thermal-hydraulic performance of the horizontal heat exchanger for PCCS as well as an overview of the whole investigation plan.

2. PCCS

2.1 Heat Removal Performance

PCCS using heat exchangers have been proposed for SBWR/ESBWR and SWR1000.[1-4] For the SBWR, heat exchangers for isolation condenser (IC) were considered conveniently usable as those of PCCS.[6] Following international developmental study for the SBWR/ESBWR, a vertical in-tube heat exchanger has been recongized to be applicable for a next-generation BWR in JAPAN[5] too as a quasi-proven component. A conventional horizontal U-tube heat exchanger, however, has emerged as another candidate based partly on the consideration of seismic-proof and possibility for cost reduction as a system including PCCS water pool, while it has been considered unsuitable primarily because of lack in the experiences about the in-tube steam condensation behavior; i.e. condensate drain with non-condensable gases.

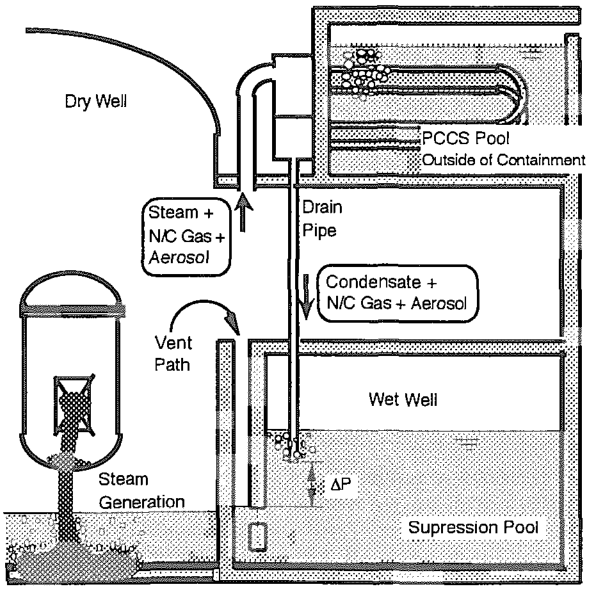

Fig. 1 Schematic of PCCS Operation

PCCS of interest is a once-through system that directly connects drywell (DW) to wetwell (WW) as shown in **Fig. 1**. There is no return line to DW, which was included in the SBWR design with GDCS (gravity drain cooling system). Steam generated in DW is driven through the PCCS heat exchanger with non-condensable gases by the pressure difference between DW and WW; namely by the water head difference ΔP between two elevations: the top of main vent pipe opening and the bottom of PCCS drain pipe. PCCS removes heat by steam condensation in the heat exchanger, and drains condensate and non-condensable gas into WW suppression pool (S/P) respectively by gravity and pressure difference. During severe accidents, aerosols including fission products would enter the PCCS heat exchanger, being drained with condensate.

Since the driving force for the PCCS operation (ΔP, **Fig. 1**) is limited by the plant geometrical configuration, the differential pressure across the heat exchanger should be less than a limiting value; i.e. ~2 kPa. Steam-gas mixture in DW enters WW through main vent line when the DW-WW pressure difference far exceeds this condition. Please note that most of steam enters WW through the main vent line during LOCA blowdown phase or at the incipience of lower head failure by high-temperature melt when the steam generation rate in DW is large. During such transients, steam flows through PCCS at maximum flow rate possibly by transporting uncondensed steam into WW S/P. Heat input to S/P through the main vent will be switched off when the DW-WW pressure difference becomes lower than the above criterion following the decrease in the steam generation rate in DW. PCCS pool is a final heat sink under such conditions.

The pressure difference across the vertical heat exchanger designed for ESBWR/SBWR has been known to be small because it is composed of large diameter short tubes.

2.2 In-Tube Condensation Behavior for Horizontal Heat Exchanger

Many researchers have investigated in-tube condensation for horizontal tubes.[9-16] However, there were no investigations that fully cover the PCCS conditions of interest

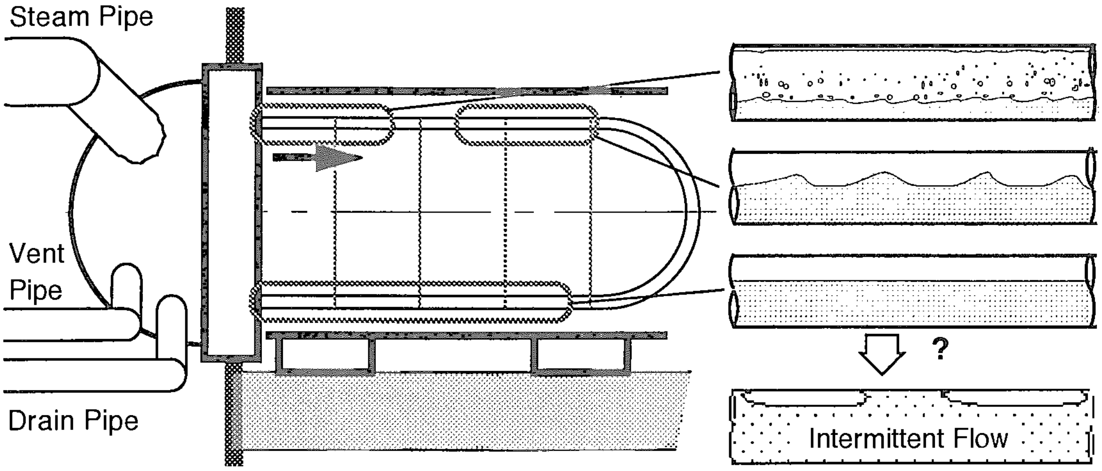

Fig. 2 Expected Flow Regimes in PCCS

where steam condensation takes place at pressures ranging from atmospheric to 0.7 MPa under influences of non-condensable gas.

Several flow regime maps have also been proposed based on experiments, but only for pure steam system where gas phase vanishes at the tube exit in most cases.[17-20] Flow regimes would be different from such observation because non-condensable gas would stagnate near the tube exit and in the outlet plenum in the PCCS of interest, even when pure steam enters the tubes. Typical flow regimes would be annular and/or annular mist, wavy and smooth stratified according to the gas velocity which decreases along the length of the tube as shown in **Fig. 2.**

One of the major concerns here have been the flow regime transition from separated flows such as wavy and/or smooth stratified to intermittent flows such as plug and slug in the tubes, since it may degrade the PCCS heat removal performance greatly because of an increase in the pressure loss across the water-plugged tubes and a oscillative pressure response. Lack in such fundamental knowledge about the heat exchanger performance may have limited the applicability of the horizontal heat exchanger to PCCS.

2.3 Approach of Investigation

Based on the survey of investigation status above, JAERI started to study the total performance of horizontal heat exchanger for the PCCS as shown in **Fig. 3.** First, JAERI performed RELAP5 code analyses to obtain preliminary information about the fundamental experiments based on assumed PCCS operation conditions. In parallel, JAERI performed design and manufacture of the test facility for the fundamental experiments, and performed air/water two-phase flow visualization experiments to study the flow response in the U-bend part, because the condenser tube of the test facility for fundamental experiments is SUS-made.

In the fundamental experiments, parameter experiments will be performed to observe in-tube condensation and hydraulic behavior in a single horizontal U-tube co-axially cooled by subcooled coolant. The influence of secondary boiling and gas vent behavior will be studied as separate-effect tests by slightly modifying the test facility. As such, data base will be prepared for model development for better predictions of the perfor-

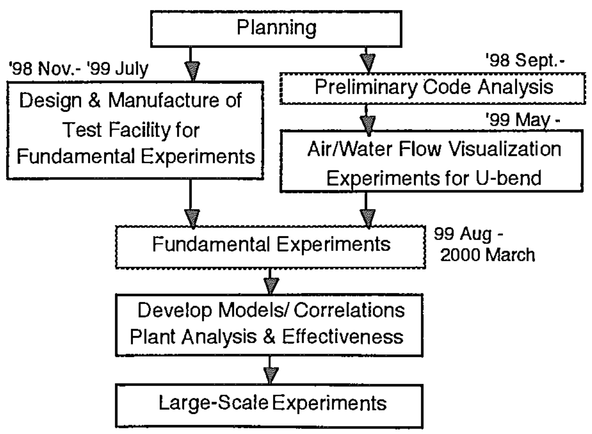

Fig. 3 Investigating Plan

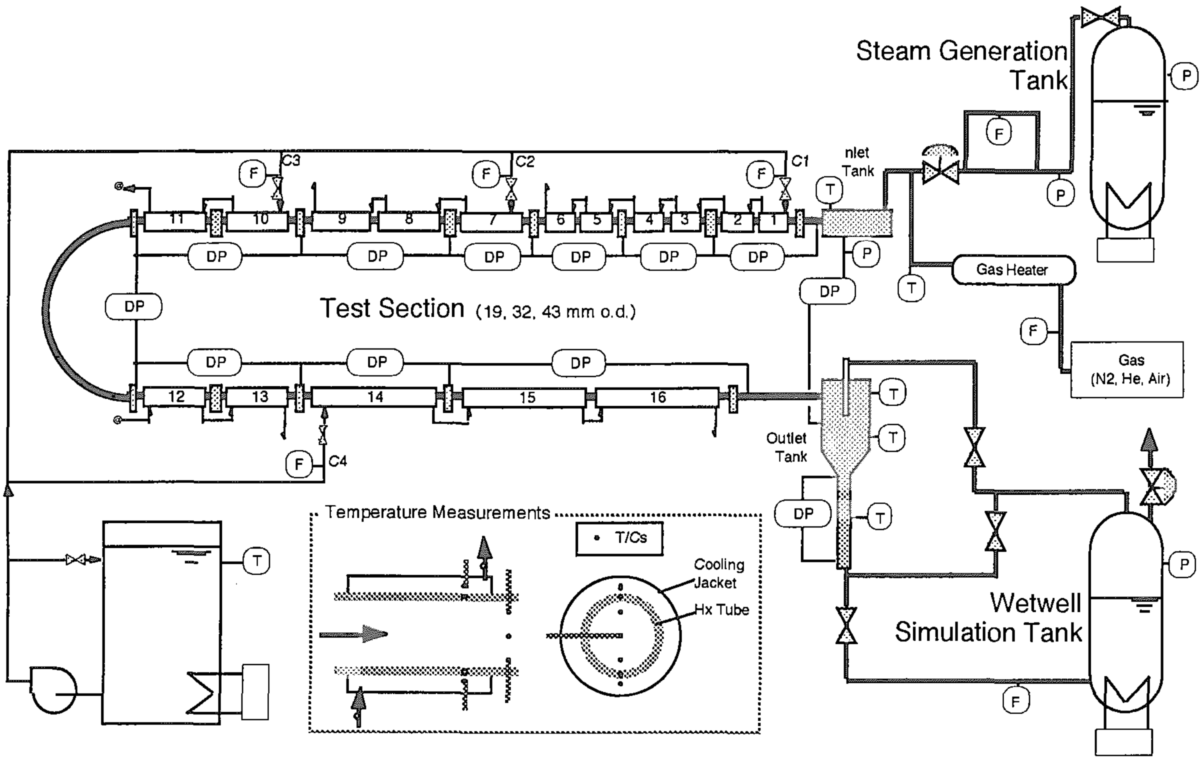

Fig. 4 Schematic of Test Facility for Fundamental Condensation Experiments

mance of the horizontal heat exchanger of PCCS by the aid of code analyses.

A large-scale tube bundle experiment will be performed once the horizontal heat exchanger is recognized feasible from the fundamental experiments and predictive analyses by computer codes being modified by the developed models.

3. Experiment

3.1 Facility

The facility is located in the ROSA-V/LSTF in JAERI with three test sections made of SUS304 with different tube outer diameters of 19.0, 31.8 and 42.7 mm. Schematic of the facility is shown in **Fig. 4**. Steam generated in 5 m^3 tank is provided to the test section inlet tank after slightly superheated by a couple of valves and trace heaters (not shown). Non-condensable gas such as nitrogen (N_2) and/or helium (He) to simulate hydrogen (H_2) was mixed with steam after temperature control through a gas heater. Flow rates of steam and gas were measured using eddy flowmeters and mass-flowmeters respectively.

The test section was composed of 16 segments with a co-axial cylindrical cooling jacket. Total cooling length was 4 m for both upstream and downstream horizontal legs. Length of cooling jacket (0.25, 0.5 and 1 m) was increased along the test section considering the decrease in condensation rate. The test section was divided into four groups of segments, each of which had an individual secondary flow control for better simulation of cooling in a water pool. Slightly pressurized subcooled water (< 60 °C) was provided to the cooling jacket to measure the amount of removed heat in each jacket. The influence of secondary boiling condition in a tube bundle such as enhancement by flow turbulence and/or degradation by steam blanketing will be investigated by using a special segment where primary steam is routed and injected into the secondary coolant. Horizontal level of the test section tube was carefully checked by using a transparent vinyl tube U-manometer.

Condensate and non-condensable gas drained first into an outlet tank and then travelled down to wetwell simulation tank (5 m^3) through a drain piping. Demineralized water was used for both primary and secondary sides.

In each cooling jacket, primary and secondary coolant and wall surface temperatures were measured at nine locations in total. As for primary side, three sheathed thermocouples (T/Cs, 1.6 mm o.d.) were inserted from top, side and bottom of tube on the same plane normal to the flow axis. Center T/C was inserted such that the tip is located on the flow axis. Two other T/Cs were inserted into the tube by ~5 mm from the wall. To measure the tube outer surface temperatures, two sheathed T/Cs (0.5 mm o.d.) were embedded in the tube wall at the tube top and bottom such that the sheath surface was flush to wall outer surface which faces to secondary coolant. The tip of T/Cs was brazed to the tube wall on the same plane as the secondary coolant T/Cs. The secondary coolant temperature was measured by four sheathed T/Cs at the inlet and outlet of the jacket and at two locations adjacent to the wall surface T/Cs. These T/Cs were in-situ calibrated by furnishing steam to the test section at several pressures under adiabatic (vacant secondary) conditions.

Heat loss of the test section was confirmed to be very low from the amount of condensate in such characterization experiments.

3.2 Experimental Conditions

Major experimental parameters were the tube geometry, primary fluid and secondary cooling conditions as shown in **Table 1**.

Figure 5 shows a typical temperature data obtained in shakedown tests using 31.8 mm tube under nominal conditions; 0.7 MPa, 1% decay power (≈ 100 kW/tube), 1% N_2 gas partial pressure. Steam-gas mixture velocity at tube inlet was ~19 m/s. Steam was totally condensed in ~6 m* in this experiment. (*Note: Distance from Tube Inlet = Hx/jacket + non-Hx tube length)

Table 1 Experimental Conditions

Geometrical Conditions		Parameters for RELAP5 Code Analyses
Tube O.D. (mm)	19.0, 31.8, 42.7	31.8
Hx Length (m)	4 x 2 = 8	Same
U-bend Radius (m)	0.3	Same
U-bend Inclination	-5°, -45°, -90°	0°, -5°, -90°
Flow Conditions		
Primary Pressure (MPa)	0.2 - 0.7	0.7 (exit)
Inlet Gas Velocity (m/s)	10 - 30 (31.8 mm tube)	20
Gas Concentration (%)	0 - 20 (partial press.)	1
Secondary Coolant Temperature (K)	333 (Inlet)	Same
Secondary Boiling Condition in a Bundle	Special segment with steam injection	N/A

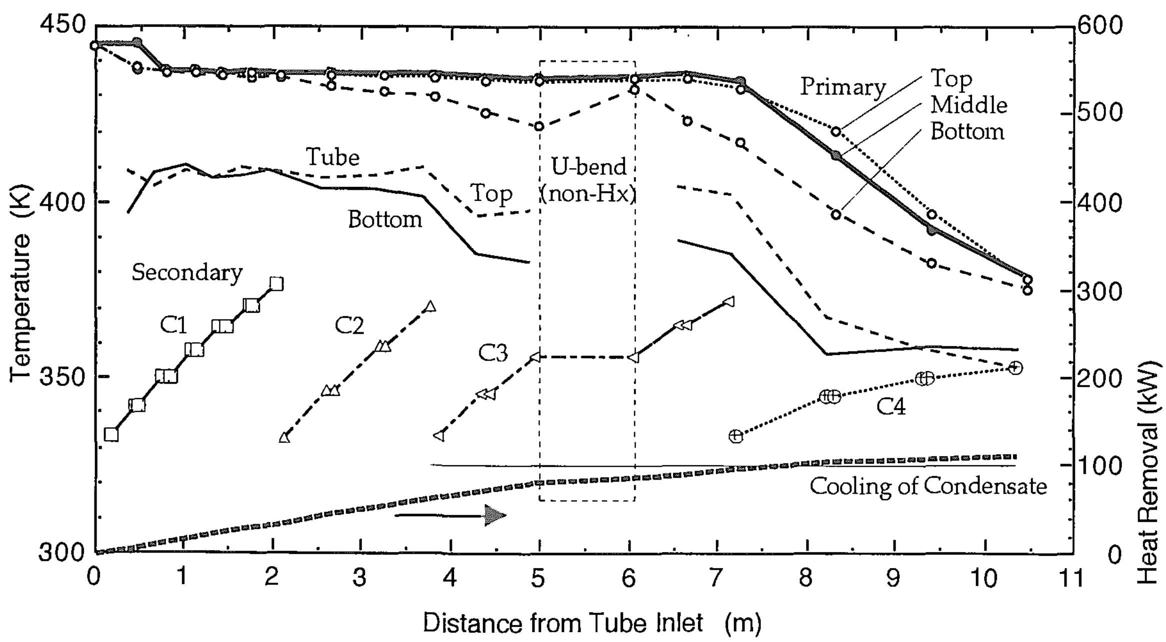

Fig. 5 Typical Temperature Data (Shakedown Test for 31.8 mm o.d. tube)

4. Preliminary Code Analysis

4.1 Calculation Conditions

Preliminary pre-test analyses of the condensation heat transfer in a simulated horizontal U-tube were performed using RELAP5/MOD3.2.1.2 code[21] to expect the experimental outcomes. The code employs Nusselt, Shah and Chato correlations[9-11] for the prediction of steam condensation respectively under laminar and turbulent flow conditions and a modification to Nusselt for laminar film flow in a horizontal tube. A correlation to predict condensation degradation because of non-condensable gas by Ueno et al.[14] was incorporated into the code, while a correlation in the original code; Colburn-Hougen,[22] was not used. The correlation by Ueno et al. is based on experiments simulating a horizontal steam generator of NP-21 as a part of the passive safety features during accidents/transients, thus for low pressure (< ~0.4 MPa) and small-diameter (~19 mm) tube conditions.

The code analyses were performed for the conditions noted in **Table 1**.

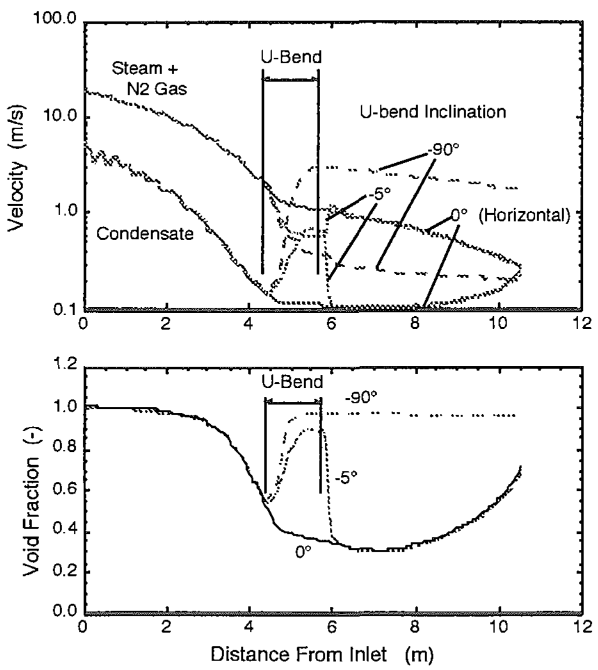

Fig. 6 Comparison of Calculated Fluid Velocities and Void Fractions for Different U-bend Inclinations (31.8 mm tube)

4.2 Calculated Results

Figure 6 compares the calculated gas and liquid velocities and void fractions in terms of distance from tube inlet obtained for three U-bend inclinations; 0°, -5° and -90°. There was no difference in the upstream horizontal leg among three cases. Velocities of both phases decreased monotonically along the length of the tube for both phases. Maximum velocity of condensate film was ~6 m/s at the tube inlet while gas velocity was ~20 m/s. In the upstream horizontal leg, liquid level of condensate reached almost to the tube axis around the connection to U-bend in the two "inclined" cases. Liquid velocity increased as well as the void fraction in the "inclined" cases because of the acceleration in the U-bend. In the "horizontal" U-bend case, on the other hand, these two parameters continued to decrease monotonically. Gas phase velocity in the "inclined" cases decreased in the downstream of the U-bend, because the cross sectional area increased and steam condensation almost completed in the upstream leg, thus gas phase is mostly composed of non-condensable gas.

In the downstream leg, liquid level increased, and started to decrease after the void fraction recorded the minimum of ~0.3 in horizontal and -5° inclined cases because of gravity drain towards the tube exit. In the -5° inclined case, the condensate velocity increased being accelerated in the U-bend temporarily, but decreased suddenly to the value of the horizontal case around the downstream leg inlet. This response looks similar to hydraulic jump. The small inclination of U-bend has little effect onto the hydraulic behavior. In the -90° inclined case, on the other hand, the condensate velocity increased very much** in the U-bend and decreased gradually in the downstream leg by the wall friction until the tube exit as super-critical flow that Froude number exceeds well 1.0. This result indicates that fluid acceleration in the U-bend has no influence to the upstream leg behavior, but controls the flow condition in the downstream leg, depending on elevation change between the upstream and downstream legs.

** Note that velocity in Fig. 6 is presented in semi-Log co-ordinate.

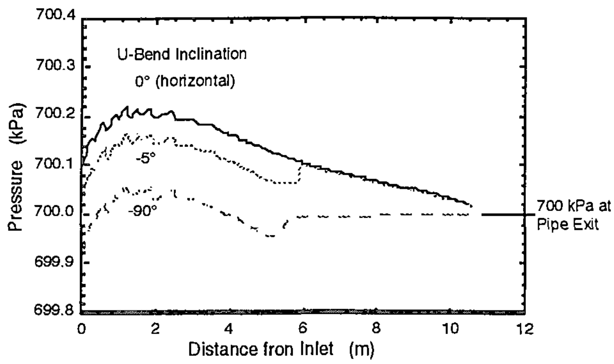

Fig. 7 Comparison of Calculated Static Pressures for Different U-bend Inclinations (31.8 mm tube)

Figure 7 compares the static pressures in terms of distance from the tube inlet. The calculated pressures first increased around the tube inlet probably because of significant condensation, while they decreased monotonically afterwards in the upstream leg. In -5° inclined case, a sudden increase in the pressure occurred at the sudden level increase around the inlet of the downstream leg because of acceleration of gas flow. In -90° inclined case, decrease in the pressure in the downstream leg was small because gas flow velocity is very small; smaller than liquid velocity. This result indicates that the condensate acceleration in the U-bend with large level difference between upstream and downstream legs is favorable to suppress the pressure loss in the heat exchanger.

In summary, the preliminary calculations suggest that the horizontal U-tubes would be promising to use for the PCCS heat exchanger by the complete steam condensation with small differential pressure across the unit under an assumed severe accident condition.

5. Conclusions

JAERI and JAPC started a verification study for the performance of a horizontal heat exchanger type PCCS for next-generation BWR as a cooperative study in 1998. A test facility with a horizontal single U-tube was constructed in JAERI in July, 1999 to investigate fundamental in-tube condensation behavior in the horizontal heat exchanger. Major experimental parameters are tube diameter, primary pressure, steam flow rate, composition and amount of non-condensable gas and secondary cooling conditions. Preliminary test results obtained under assumed accident conditions; steam generation rate ≈ 1% core power, concentration of N_2 gas of 1% and containment vessel pressure of 0.7 MPa, indicated a total steam condensation in ~6 m from the tube inlet a 31.8 mm o.d. test section.

Preliminary pre-test analyses were performed using RELAP5/ MOD3.2.1.2 code to expect the experimental outcomes. A correlation by Ueno et al. was incorporated to predict degradation of steam condensation by non-condensable gas. The calculated results indicated that the PCCS using horizontal U-tubes is promising with a small differential pressure between inlet and outlet plenum.

Experimental data will be accumulated, and models and correlations will be developed for a better prediction of condensation and degradation by non-condensable gas in the horizontal heat exchanger for PCCS based on the experimental data. System and multi-dimensional analyses will be performed using computer codes with the developed models and correlations. Large-scale experiments will then be performed to clarify the total responses of the horizontal heat exchanger including multi-dimensional phenomena that are necessary for system response analyses.

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