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Studies on the behaviour of a passive containment cooling system for the Indian Advanced Heavy Water Reactor

A passive containment cooling system has been proposed for the advanced heavy water reactor being designed in India. This is to provide long term cooling for the reactor containment following a loss of coolant accident. The system removes energy released into the containment through immersed condensers kept in a pool of water. An important aspect of immersed condenser's working is the potential degradation of immersed condenser's performance due to the presence of noncondensable gases. An experimental programme to investigate the passive containment cooling system behaviour and performance has been undertaken in a phased manner. In the first phase, system response tests were conducted on a small scale model to understand the phenomena involved. Tests were conducted with constant energy input rate and with varying energy input rate simulating decay heat. With constant energy input rate, pressures in volume V_1 and V_2 reached almost steady value. With varying energy input rate V_1 pressure dropped below the pressure in V_2. The system could efficiently purge air from V_1 to V_2. The paper deals with the details of the tests conducted and the results obtained.

Untersuchung des passiven Containment-Kühlsystems des Indischen Advanced Heavy Water Reactor. *Ein passives Containment-Kühlsystem wird vorgeschlagen für den fortgeschrittenen Schwerwasserreaktor, der zur Zeit in Indien entwickelt wird. Auf diese Weise wird bei einem Störfall durch Kühlmittelverlust eine Langzeitkühlung für das Reaktor-Containment bewirkt. Das System führt durch Tauchkondenser Energie in einen Wassertank ab. Ein wichtiger Aspekt bei dieser Methode ist die potentielle Degradation der Tauchkondenser-Leistung durch das Vorhandensein nichtkondensierbarer Gase. Ein experimentelles Programm zur Untersuchung des Verhaltens und der Leistung des passiven Containment-Kühlsystems wurde in verschiedenen Phasen durchgeführt. In der ersten Phase wurden System-Response-Tests mit einem verkleinerten Modell durchgeführt, um so die beteiligten Phänomene zu verstehen. Die Tests wurden sowohl mit konstanter Eingangsenergie wie auch mit variablen Eingangsenergien zur Simulation des Wärmerückgangs durchgeführt. Bei konstanter Eingangsenergie befanden sich der Druck im Volumen V_1 und V_2 fast im Gleichgewicht. Bei verschiedenen Eingangsenergien fiel der Druck in V_1 unter den Druck in V_2 und das System konnte wirkungsvoll Luft von V_1 nach V_2 abführen. In der Arbeit wird ausführlich über die durchgeführten Tests und deren Ergebnisse berichtet.*

1 Introduction

The Indian Advanced Heavy Water Reactor (AHWR) being designed is a vertical pressure tube type boiling light water cooled and heavy water moderated reactor. Key features of the reactor [1] include thorium based fuel, negative void coefficient of reactivity and passive systems for energy removal. The 750 MW_t reactor uses $(Th-U^{233})O_2$ and $(Th-Pu)O_2$ as fuel. In AHWR, heat generated in the fuel is removed by natural circulation of coolant.

Increasing awareness towards safety and the experience gained in the past have led to the incorporation of a number of passive safety systems in the new generation of nuclear reactors being designed. These systems depend on the natural laws of gravity, thermal hydraulics and physics and do not require the intervention of operators or use of externally actuated electrical or mechanical devices. One such system envisaged for long term containment cooling of advanced reactors following a postulated Loss of Coolant Accident (LOCA) is the Passive Containment Cooling System (PCCS). The purpose of the PCCS is to limit the containment pressure to a value below a predetermined level and to achieve a walk-away period without operator action.

Investigations on several concepts of passive safety systems for the long term heat removal from the containment have been carried out in different parts of the world. In these systems the transfer of heat from the containment building to the environment is effected by employing either evaporation of water from water pools or natural draft cooling of containment structures. In the first type the containment heat rejection through various means like suppression chamber (SC) water wall, drywell water wall, Isolation condensers etc. have been contemplated in advanced boiling water reactors [2]. The Westinghouse AP-600 reactor [3] utilizes the second concept in which the heat from the containment is removed by cooling of steel containment structure by natural convection of air in counter-current to an evaporating water film.

In Indian AHWR, two alternate designs for the passive cooling of containment are under consideration. In first alternative, a passive containment cooling system similar to that adopted in SBWR has been considered. The SBWR [4] utilises the isolation condenser technology used for decay heat removal from BWRs. This technology is extended to long term, post accident containment heat removal. This system removes energy released into the containment through immersed condensers kept in a pool of water located at higher elevation. In second alternative, cooling coils of PCCS is connected to a water pool above it. The containment steam condenses on the outer surface of tubes. Water from the pool circulates through these tubes by natural circulation [5]. Studies

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are undertaken to compare the effectiveness of the two alternatives. The experimental programme for first alternative has been described in this paper.

2 Passive containment cooling system

The concept of double containment has been adopted for AHWR. The containment structure consists of a cylindrical prestressed cement concrete (PCC) primary containment with PCC dome and a secondary containment of reinforced cement concrete (RCC) structure completely surrounding the primary containment. The walls of the containment are not lined with steel. The annular space between primary and secondary containment envelopes is provided with a purging arrangement to maintain a negative pressure in the space, so as to prevent ground level release of radioactivity to the environment during accident. The reactor building primary containment is divided into two volumes: volume V_1 (dry well), housing the reactor coolant system and volume V_2 (wet well) partly filled with water whose function is to condense the steam in case of loss-of-coolant accident. The free space of the volume V_2 serves as a chamber for accommodating noncondensables. The two compartments are connected through pipes (main vent shafts) and through the vent line of PCCS that are submerged in the water of volume V_2. In the initial period of accident when the pipe in the reactor coolant system ruptures, the steam mixes with noncondensables present in the volume V_1 and enters the suppression pool through the main vent shafts. The steam condenses in the suppression pool which results in suppression of pressure of volume V_1. When the differential pressure between volume V_1 and V_2 reduces below a value corresponding to the submergence depth of main vent shaft, the flow through the main vent shaft stops. Since, the PCCS vent line submergence is much less than main vent shaft, the containment heat removal through the PCCS continues. The energy removal is required to reduce containment pressure below a design limit to reduce ground level release of radioactivity due to the leakage. The PCCS is designed to operate effectively for 72 hours. Some of the technical data are presented in Table 1.

A simplified diagram of the PCCS of first alternative is shown in Fig. 1. The immersed condenser comprises of a large number of vertical tubes connected to horizontal cylindrical headers at the top and bottom. The IC is immersed in a large pool of water located in the IC Pool at a high elevation as shown in the figure. The heat released in 72 hours in the containment is stored in the water pool in the form of sensible heat unlike SBWRs. The description of the functioning of the PCCS as presumed before the experiments is as follows. Steam-noncondensable gas mixture enters the IC from volume V_1 (drywell) of the primary containment, following LOCA, through a line which has no valve. Steam is condensed in the IC and the condensate flows by gravity to a water pool in volume V_1 from the bottom header of the IC. The noncondensable gases are led to the water pool in volume V_2 (wetwell) through a vent line submerged in water. Due to the inflow of noncondensables into volume V_2, the pressure of V_2 increases. When the pressure in volume V_2 exceeds the pressure in volume V_1 by a preset value the vacuum breaker opens and the noncondensables return to volume V_1. The vacuum breaker is provided to ensure that the pressure of volume V_1 does not fall significantly below the V_2 pressure. This enables to maintain the containment structural integrity. When the differential pressure between volume V_2 and V_1 reduces to a preset value the vacuum breaker closes. The continued accumulation of noncondensables in IC causes degradation of the performance of the IC, resulting in pressure rise in volume V_1. This may again cause the flow of noncondensables to volume V_2, depending on the conditions. The PCCS is always available for the containment heat removal. The differential pressure between the volumes V_1 and V_2 initially provides the driving head for the steam-gas mixture flow through the IC. The heat removal capability of PCCS is affected mainly by the flow path pressure loss, noncondensables inside the containment and heat transfer coefficients in the pool and the IC.

Table 1. *Important technical data of Indian AHWR*

Parameter	Unit	Value
General plant data		
Reactor type		Vertical pressure tube BWR
Fuel material		$(Th–Pu)O_2$ and $(Th–^{233}U)O_2$
Reactor thermal power	MW_{th}	750
Reactor Pressure	Mpa	7
Primary Containment		
Type		Pressure suppression
Overall form		Cylindrical
Dimensions (diameter/height)	m	44/72
Free air Volume		
V_1 volume	m^3	9724
V_2 volume	m^3	53240
Design pressure	kPa	359
Design temperature	°C	156
PCCS IC		
Area	m^2	135
Tube outer diameter	m	0.0483
Tube length	m	1.6

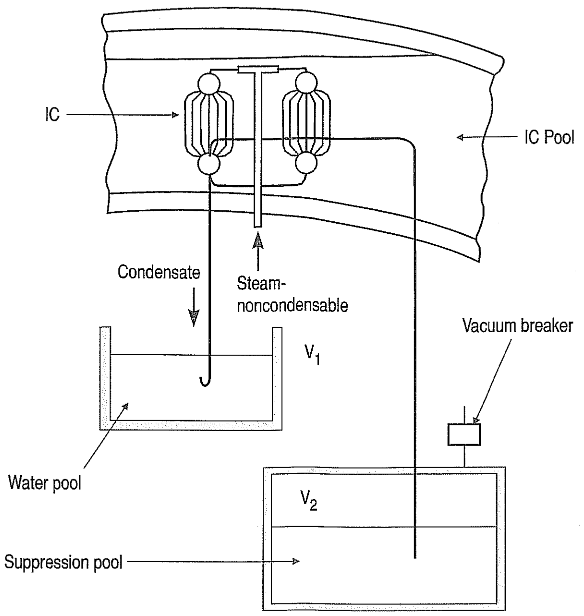

Fig. 1. Passive containment cooling system with immersed condensers

3 Past work

Oikawa et. al. [2] evaluated the heat removal performance of several passive containment cooling systems following a Loss Of Coolant Accident (LOCA) and indicated that PCCS with isolation condenser may be the best option for long term containment heat removal. *Otonari* et al. [6] had carried out transient analysis considering PCCS with isolation condenser in case of main steam line break by a computer code TOSPAC. The analysis was also extended to cover a wide range of break spectra to confirm the isolation condenser effectiveness. Yokobori et al. [7] performed system response test of passive containment cooling system with isolation condenser on a scale model. In their studies, they carried out two types of tests, viz. nitrogen venting test and isolation condenser system response test. The nitrogen venting test was conducted with constant power (steam input constant with time) conditions while in the system response test the power was controlled to simulate the decay heat. They concluded that the steam and nitrogen mixture are well separated in the bottom header of the isolation condenser and then the separated nitrogen is effectively vented to the suppression chamber (SC). In system response test it was observed that after most of the nitrogen gas is vented to the SC, the isolation condenser achieved an improved heat removal capacity. Subsequently, because of continuous decrease in decay heat, the isolation condenser heat removal rate overcomes decay heat and the drywell (DW) pressure decreases gradually below the SC pressure.

Yokobori et al. [7] had observed a sudden drop in DW pressure from maximum to a pressure below the SC pressure in nitrogen venting test. They have not stated the reason for this sudden drop. In system response test even though most of the nitrogen was vented to SC in one hour and steam input rate (decay heat) was gradually reducing, the sudden drop in DW pressure was not noticed (vacuum breaker opening occurred at about 10,000 seconds) as reported in the nitrogen venting case. After the initial vacuum breaker opening, number of vacuum breaker openings are encountered. It was noted that though the vacuum breaker opened a number of times the vent shaft was never cleared. This suggests that the nitrogen entering from the SC to DW after the first vacuum breaker opening had not returned to SC through isolation condenser again and appreciable degradation of isolation condenser might not have occurred. It seems that the multiple openings of the vacuum breaker was due to the reduction of DW pressure caused due to the reducing energy input into DW. *Banduski* et. al. [8] had carried out a large number of thermal hydraulic tests in large scale PANDA facility to examine the long term LOCA response of PCCS for General Electric (GE) SBWR. The PCCS was demonstrated to be a reliable system for long-term containment cooling.

The IC is an important component of PCCS from the design point of view as the condensation of steam gets greatly inhibited in the presence of noncondansable gases. The steady state tests to investigate the steam condensation in the presence of noncondensables have recently been carried out on single SBWR isolation condenser tube by many researchers. *Vierow* et al. [9], *Khun* et al. [10] and *Siddique* et al. [11] measured the local heat transfer coefficient along a vertical tube and correlated the results in terms of the local mixture Reynolds number and local bulk air mass fraction. The relative effect of gases heavier than steam and lighter than steam has also been investigated. *Nagasaka* et al. [12] had performed condensation experiments on 1:400 scale model of the isolation condenser of SBWR in the presence of nitrogen. The results were presented in terms of degradation coefficient as a function of nitrogen mole fraction at the inlet of the tube. *Masoni* et. al. [13] conducted experiments on a full scale model of isolation condenser of PCCS of SBWR. The condenser efficiency as a function of air mass fraction is presented. The effect of superheating is found to be negligible.

4 Test objectives

As PCCS with IC has been considered as one of the alternatives for AHWR, it became necessary to understand the behaviour of PCCS in detail and to establish the efficiency of the system. The main objectives to carry out the experimental studies are as follows.

- To confirm the working principle of PCCS
- To study the system behaviour for constant and varying energy input into volume V_1.
- To study the cause of multiple openings of vacuum breaker.
- To study the effect of noncondensable gas on condensation heat transfer.
- Development of a theoretical model based on the observed phenomena.

An experimental programme to investigate PCCS behaviour and performance has been undertaken in a phased manner. In the first phase, system response tests were conducted on a small scale model to understand the phenomena involved. As the degradation of heat removal capacity of IC due to the presence of noncondensables is an important aspect of IC functioning, separate effect tests on full scale tubes of IC of AHWR are planned to be carried out in the second phase. Simultaneously, work on the development of theoretical models is taken up. A brief description of the system response test conducted is given below.

5 Test set-up

Tests to study the system response behaviour have been conducted on a small scale model of the PCCS (see Fig. 2), The volume scaling of the set-up is approximately 1:3000. Elevation and hydraulic resistances could not be simulated in this small scale model. The configuration of IC has been simplified as shown in Fig. 2. The upflow tube is thermally insulated. Instead of natural circulation, a small forced flow of water is maintained in the secondary side of IC. Air has been used as the noncondensable gas during the tests. The steam-air mixture from volume V_1 flows to IC steam box or upper header. The noncondensable gas vent line runs from IC water box or lower header to the suppression pool. The condensate from the IC water box flows to a condensate collection plenum

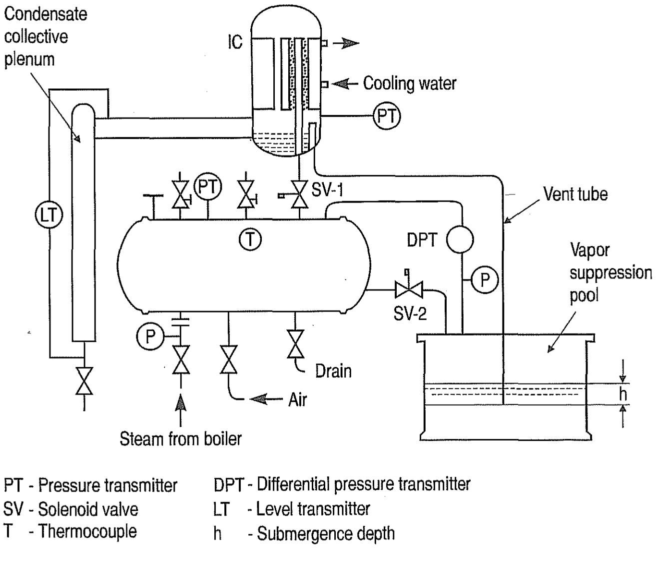

Fig. 2. Experimental set-up

which is vented at the top to the gas space of the IC water box. The level of water in the plenum is maintained at an almost constant value using a valve in the drain line from the condensate plenum. Air is injected into volume V_1 from a compressor and steam is introduced from a boiler.

The volume V_2 is connected to the IC through the gas vent line. The vacuum breaker between the volumes V_1 and V_2 has been simulated by a solenoid valve (SV-2) and a transmitter provided for the differential pressure measurement between the two volumes. Whenever the pressure of V_2 exceeds the pressure of volume V_1 by a specified amount, the solenoid valve opens and air flows back from volume V_2 to V_1. When the differential pressure reduces to a set value, the solenoid valve closes.

The pressures in volumes V_1, V_2 and IC water box are measured by pressure transmitters. The level in the condensate collection plenum is measured by a level transmitter. The temperature of volume V_1 is measured at three different locations by thermocouples installed inside the vessel. Air partial pressure P_a in volume V_1 is calculated as the difference between the total pressure P_t and steam saturation pressure P_s. The flow of steam into the volume V_1 is estimated approximately by the condensation rate of steam in the IC and condensation in volume V_1 due to heat loss. Variation in the steam flow rate into volume V_1 is estimated by measuring the pressure drop across a restriction in the steam inlet line.

6 Test conditions

Tests have been conducted under the following conditions:

- By maintaining a constant steam flow rate into volume V_1.
- By varying the steam flow rate into volume V_1 as per decay heat curve. Variation of steam flow rate with time is depicted in Fig. 3.

Steam flow rate into the system at time t = 0 is decided based on energy input rate into the containment one hour after occurrence of LOCA. This is because, in the initial period of transient, the V_1 pressure rises sharply which causes steam venting through main vent shaft connecting volume V_1 and V_2. The submergence depth of this vent shaft is higher than the submergence depth of vent line in PCCS. After a period of time, the venting of steam through main vent shaft becomes ineffective due to reduction in differential pressure between volume V_1 and V_2. From this time onwards energy is removed only through PCCS.

In both the above cases, initially volume V_2 was maintained at atmospheric pressure. Steam flow rate into volume V_1, air content and submergence depth of vent tube in the suppression pool were varied during the tests. The range of parameters used as initial conditions during the tests are given in Table 2.

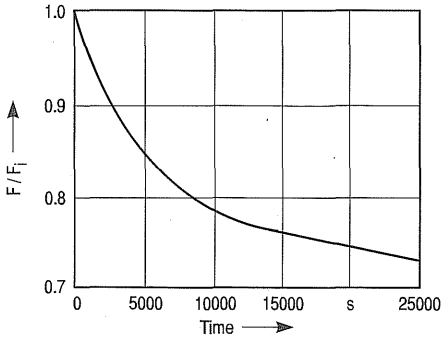

Fig. 3. Variation of steam flow rate with time

Table 2. Initial conditions

Parameter	Unit	Range
Pressure in volume V_1	bar	1.17–1.30
Pressure in volume V_2	bar	1.0
Pressure in IC	bar	1.0
Flow rate (F_i)	Kg/s	0.0017–0.0038
Air Content in Volume V1	%	4–15
Submergence depth	mm	300–600

7 Test procedure

Volume V_1 is initially isolated from the IC and volume V_2. Air was purged from volume V_1 through the exhaust line by supplying steam from the boiler for a sufficiently long time. During this process, volume V_1 vessel also got heated up. After the air was removed, the exhaust line was closed. The volume V_1 was pressurised to the required initial partial pressure of air by introducing air. The air line was then closed. Steam was then supplied to the volume V_1 to achieve the desired initial total pressure. The IC and Volume V_2 were maintained at cold atmospheric condition. Tests were initiated by opening the valve between volume V_1 and IC. The valve in the steam inlet line was also opened simultaneously. Variable steam flow rate into volume V_1 was achieved by operating the valve shown in Fig. 2. Heat loss from volume V_1 was ascertained by maintaining a constant pressure in this volume with through flow of steam and measuring the amount of condensate over a period of time.

8 Results and discussions

With constant steam input to volume V_1, a number of experiments were conducted for different values of the parameters of interest. Results of two such experimental runs are depicted in Figs. 4 a and 4 b. Fig. 4 a represents a case with very low steam flow rate. In this case, because of the initial high condensation rate in the IC, V_1 pressure first decreases and then increases with reduction in condensation rate in the IC. Since the IC pressure exceeds the V_2 pressure by an amount more than the submergence depth of the vent tube, the vent tube water is driven out and air enters the volume V_2. This causes the V_2 pressure to rise. At about 3200 seconds water again enters vent tube and flow of air into V_2 stops. Beyond this time no change in V_2 pressure was observed. Volume V_1 pressure also remains almost unchanged since the energy removal rate of the IC matches the energy input rate. The tests were continued for about 10,000 seconds. Upto this time, no further change in the pressures of V_1 and V_2 was observed. Since V_1 pressure was always higher than V_2 pressure, during the test, the vacuum breaker simulator did not operate and there was no return of air from V_2 to V_1. IC water box pressure is also plotted in Fig. 4 a. It can be inferred from these observations that at about 3200 seconds, the V_1 pressure attained such a value at which energy input rate into volume V_1 matched with the energy output rate from volume V_1 mainly through the IC and heat loss. Hence, from this time onward there was no change in V_1 pressure. V_2 pressure also remained almost constant since there was no inflow into or outflow from V_2. This indicates that V_1 and V_2 pressures are likely to reach steady value with V_1 pressure higher than V_2 pressure when steam inflow rate into V_1 is constant.

Fig. 4 b depicts the results of another experiment with different values of parameters of interest. Because of higher steam flow rate the initial sharp decline of V_1 pressure, seen in the previous case, was not observed in this case. There is a small increase in V_1 pressure initially, which then starts reducing. The subsequent trends of the pressure curves are observed to be the same as in the earlier case. Though the tests were conducted for a longer period (25,000 seconds) no changes in V_1 and V_2 pressures were observed, neither the vacuum breaker simulator operated for reasons described above.

Figs. 5 a to 5 e depict the pressure transients in V_1 and V_2 for variable steam flow rate for different values of submergence depth, initial steam flow rate and initial air content. It may be observed from Fig. 5 a that the pressure in V_1 drops below the pressure in V_2 and the vacuum breaker opens (indicated by arrow in the figure) at around 17,000 seconds, and closes subsequently. The effect of increase in the initial amount of air in volume V_1 can be seen by comparing Fig. 5 b with Fig. 5 a. In the case shown in Fig. 5 b the vacuum breaker opens at around 15,000 seconds. However, the pressures in both the volumes are found to be higher for the case of higher initial air content. Due to the limited periods over which the tests were conducted, subsequent vacuum breaker opening could not be obtained. These observations indicate that high-

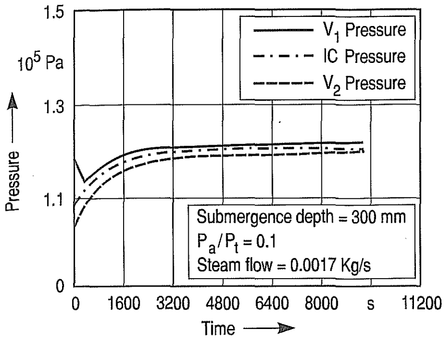

Fig. 4 a. Pressure transients with constant steam flow rate

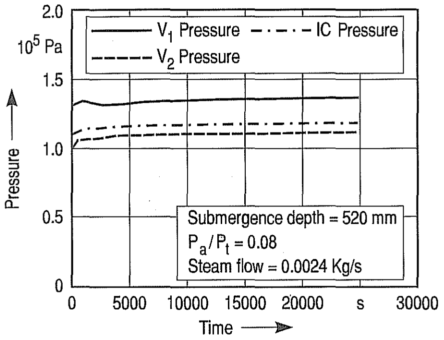

Fig. 4 b. Pressure transients with constant steam flow rate

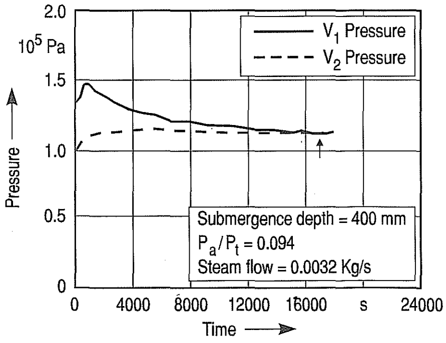

Fig. 5 a. Pressure transients with variable steam flow rate

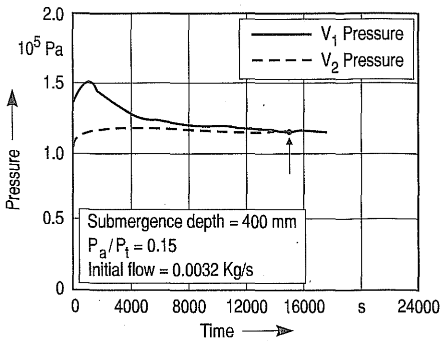

Fig. 5 b. Pressure transients with variable steam flow rate

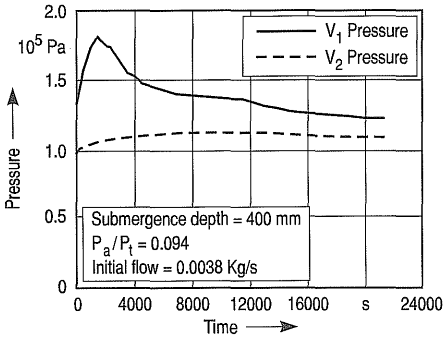

Fig. 5 c. Pressure transients with variable steam flow rate

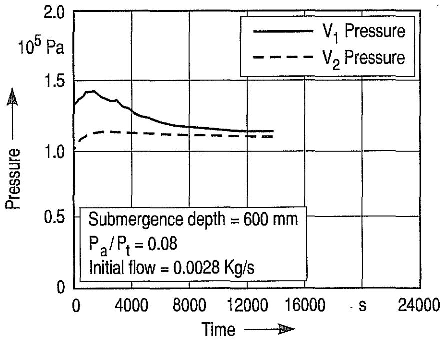

Fig. 5 d. Pressure transients with variable steam flow rate

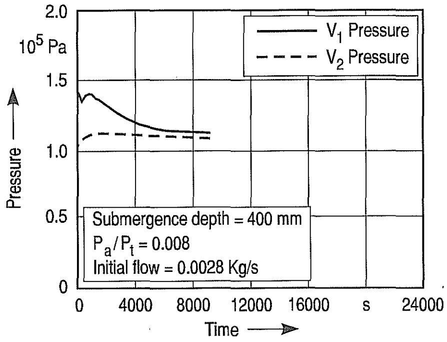

Fig. 5 e. Pressure transients with variable steam flow rate er initial air content in volume V_1 increases V_2 pressure because of large amount of air entering V_2. This also leads to increase in initial V_1 pressure. Subsequently, due to reduced steam flow rate into V_1, V_1 pressure decreases causing the vacuum breaker simulator to open.

Comparison of Fig. 5a with Fig. 5c reveals the effect of higher initial steam flow rate. From Fig. 5c it can be observed that due to the higher steam flow, pressure in V_1 has increased considerably, but the pressure in V_2 remains unaltered which it appears, is mainly affected by initial air content. Upto 20,000 seconds, vacuum breaker opening was not encountered. The effect of change in submergence depth is depicted in Figs. 5 d and 5 e. Increase in submergence depth leads to an increase in V_1 pressure. However, in this case also, as explained earlier no significant change of V_2 pressure was observed. For the cases depicted in Figs. 5 d and 5 e, vacuum breaker opening did not take place during the limited period for which the tests were carried out.

From the tests with varying steam input it has been observed that after air is vented to volume V_2, heat removal capacity of IC improves. Beyond this time, V_2 pressure does not change since there is no further air flow into V_2. However, since the steam input to volume V_1 is reducing and at the same time IC heat removal capacity is improved, the IC pressure and thereby V_1 pressure reduces. This finally leads to vacuum breaker simulator opening. The experimental observations indicate that the opening of vacuum breaker (reduction of V_1 pressure below V_2 pressure) is mainly due to the reduction in steam input (decay heat) with time though it is also influenced by the improvement in IC performance due to venting of noncondensable air from volume V_1 to volume V_2. The purging of air from IC to volume V_2 always occurred as long as the pressure of IC was more than summation of the pressures corresponding to the submergence depth and the pressure drop caused by the resistance offered by the flow path between IC and volume V_2. The test further indicated that the possibility of IC getting air blocked is remote. Any accumulation of air in IC will cause increase in V_1 pressure which in turn will cause flow of steam-air mixture to IC which will clear the air from IC to volume V_2.

9 Conclusions from the tests

- The tests conducted over the limited range of values of different parameters have confirmed the efficacy of the PCCS in separating the noncondensables diverting it to volume V_2 and removal of energy released into the volume V_1 of containment.
- During experiments with constant steam flow rate, pressures in volumes V_1 and V_2 reached almost steady values after the initial transients. Vacuum breaker did not open in this case since V_1 pressure was always higher than V2 pressure. The test indicated that V_1 pressure attained a value at which energy input rate into V_1 matched the energy removal rate from IC and heat loss leading to no further change in V_1 pressure.
- During the experiments with reduced steam flow rate (simulating decay heat curve) V1 pressure dropped below the pressure of volume V2, thus causing the vacuum breaker to open. The reduction of V1 pressure can be attributed to the decrease in steam flow rate and improvement of IC performance.

Nomenclature

F: Flow
F_i: Initial flow
h: Submerged depth
P_a: Air partial pressure
P_t: Total pressure
P_s: Saturation pressure

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