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Air Water Loop for investigaion of flow dynamics in a steam drum: Steady state two-phase natural circulation experiments and validation

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A B S T R A C T

Advanced Heavy Water Reactor (AHWR) is a vertical pressure tube type boiling water reactor that relies on two-phase natural circulation for heat removal from the nuclear core under normal operating as well as accidental conditions. In case of AHWR, the two-phase flow generated in the core is transported by vertical riser pipes to horizontal steam drums at the top. These horizontal steam drums provide sufficient surface area for the separation of steam water mixture purely based on gravity i.e. due to density difference between steam and water. To investigate this gravity separation phenomenon, an experimental facility known as Air-Water Loop has been designed. The facility has a scaled geometry of AHWR steam drum operating with Air-Water mixture as a working fluid. The required flow conditions for the experimental simulations are generated using air-water two-phase natural circulation in this facility. Steady state natural circulation experiments were performed where measurements on recirculation flow rates, two-phase and single phase pressure drop in various sections of the loop have been carried out. The present paper aims to describe the design aspects of the facility, pre-test calculations, steady state two-phase natural circulation experiments and assessment of measured experimental data. The experimental measurements have been predicted using a numerical model that considers various void fraction and pressure drop correlations from the literature for estimation of measured parameters.

1. Introduction

Advanced Heavy Water Reactor (AHWR) is a vertical pressure tube type, boiling light water cooled and heavy water moderated nuclear reactor (Sinha and Kakodkar, 2006). The AHWR employs two-phase natural circulation as a mode of coolant recirculation through the reactor core for removal of heat generated in fuel rod bundle in normal as well as accidental operating conditions. Fig. 1 shows the schematic of Main Heat Transport System (MHTS) of AHWR. The water boils in the core (1) and is transported to steam drum (2) situated approximately 30 m above reactor core through vertical tail pipes (3) due to buoyancy. The steam drum is a horizontal pressure vessel with circular cross-section having 4 m diameter and 11 m length. The reactor has total 452 fuel channels (4), 452 tail pipes (3) and 452 feeders (5). It has total 4 steam drums and 113 tailpipes are connected to each steam drum. The tail pipes are connected to bottom of the drum symmetrically as shown in Fig. 2. Steam gets separated in drum (6) and leaves from 4 outlets (7) at the top and separated water returns to core via 4 numer of down comers (8) connected at the bottom of steam drum. To avoid mixing of two-phase flow entering in steam drum and the separated water, vertical baffles (10) are placed around the down comer region. In order to maintain the mass inventory in MHTS, feed water is added using feed water sparger (9) in down comer region of steam drum compensating the mass of steam leaving the drum. The collapsed level for steam drum is maintained at 2.2 m at 100% full power operating conditions. Due to horizontally placed steam drum, large separation interface is available which reduces the superficial velocity of steam at separation interface. This assists for efficient gravity separation. The steam separates by gravity i.e. due to density difference between steam and water, without aid of any mechanical separators, and thus simplifies the operation of steam drum. Gravity separation also improves the economy as lesser parts involved in construction and subsequent maintenance requirements are reduced. However, the effectiveness of gravity separation depends on the amount of carryover (conveyance of liquid droplets in the steam flow to turbine). Excessive carryover leads to erosion induced corrosion of steam piping and turbine blades. As per technical guidance document on steam purity for turbine operation by The International Association for the Properties of Water and Steam (IAPWS), the amount of carryover in saturated steam from BWRs is to be limited to less than 0.1% (IAPWS TSD5-13, 2013). In the case of the AHWR, which is

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Nomenclature

A_1	upstream cross-sectional flow area (m^2)
A_2	downstream cross-sectional flow area (m^2)
Ar	non-dimensional number in Eq. (9) and is given by Eq. (10)
C_0	phase distribution parameter
D	diameter (m)
D_H	hydraulic diameter of vessel (m)
D_H^*	dimensionless hydraulic diameter of vessel given as $D_H/\sqrt{\sigma/g(\rho_l-\rho_g)}$
E_{fg}	entrainment of liquid into gas/vapor flow
e_i	error in prediction
e_m	mean error in prediction
e_{ma}	mean absolute error in prediction
f	friction factor
g	gravitational acceleration (m/s^2)
h	height above the separation interface/pool surface
h^*	dimensionless height above the pool surface given as $h/\sqrt{\sigma/g(\rho_l-\rho_g)}$
J_g	superficial velocity of gas (m/s)
J_g^*	dimensionless superficial velocity of gas given as $J_g/(\sigma g(\rho_l-\rho_g)/\rho_g^2)^{1/4}$
J_l	superficial velocity of liquid (m/s)
L	length of pipe section
$\dot{m}$	mass flow rate (kg/s)
$N_{\mu g}$	dimensionless gas viscosity number given as $\mu_g/(\rho_g\sigma\sqrt{\sigma/g(\rho_l-\rho_g)})^{1/2}$
u_m	uncertainty in measurement
U_{gl}	drift flux velocity (m/s)
K_L	local pressure drop (N/m^2)
P	pressure (N/m^2)
Re	Reynolds number
Re_m	modified Reynolds number
S	slip ratio
V	velocity (m/s)

Greek Symbols

ρ	density (kg/m^3)
μ	dynamic viscosity ($N.s/m^2$)
α	void fraction
σ	surface tension (N/m)
σ_m	standard deviation of measured values
ϵ	surface roughness (m)
ε	void fraction/Hold up
ξ_c	calculated parameter
ξ_m	measured parameter
ψ	multiplier for two phase local pressure drop
χ	flow quality given by $\dot{m}_g/(\dot{m}_l+\dot{m}_g)$

Subscripts

1ϕ	single phase
2ϕ	two phase
l	liquid
g	gas
T	total
$pool$	air-water drum pool
P	prototype
M	model

pressure tube type BWR, the design goal is set to limit the carryover below 0.03% during any load change or normal operational transients.

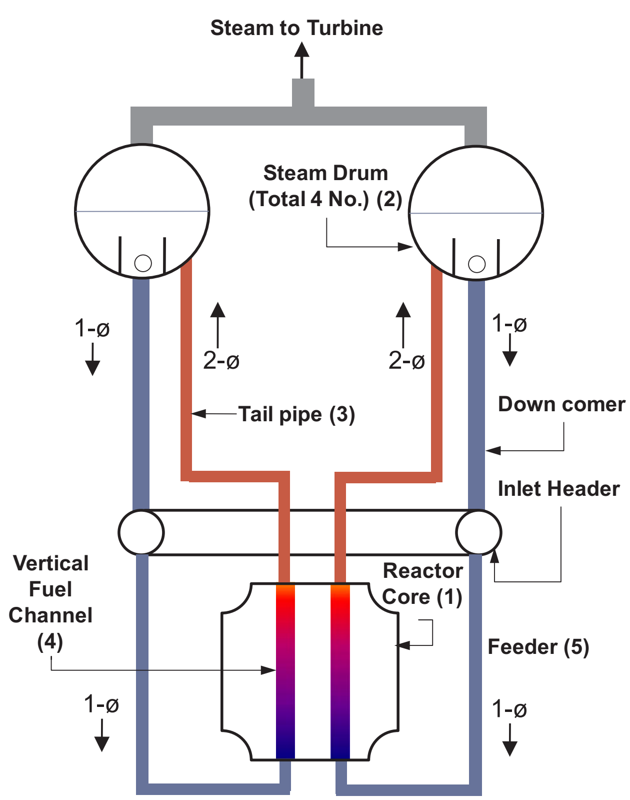

Fig. 1. Schematic of MHTS of AHWR.

Various experimental and analytical studies focused on investigation of carryover process are available in the published literature (Aiba and Yamada, 1959; Davis, 1940; Garner et al., 1954; Newitt et al., 1954; Sterman, 1958; Kolkolostov, 1952; Rozen et al., 1970). A comprehensive review on entrainment phenomenon in two-phase flow systems was carried out by Bagul et al. (2013). From the available literature it is found that most of the experimental work related to entrainment phenomenon is performed in geometry of vertical cylinder with air-water as well as steam-water. Empirical correlations available in literature are based on these experiments in simpler geometries. Validity of these empirical correlations for application in actual equipment needs to be established and experiments in relevant geometry are essential to test empirical correlations/analytical models for carryover prediction.

Another challenge for steam drum design is avoidance of carryunder i.e. bubbles getting entrained in downcomer flow, which will reduce the net buoyancy force and flow in the MHTS loop. Carryunder depends on bubble size distributions and flow patterns inside the drum. The bubble hold up in the steam drum pool also determines the swell level (location of separation interface) and thus the vapor space available above separation interface. The available vapor space above interface is an important parameter that affects the carryover phenomenon.

Previously very few experimental studies have been carried out to address the above thermal-hydraulic issues for AHWR steam drum. Studies carried out by Iyer et al. (2010) focused mainly on entrainment phenomenon in gravity separation. The experiment was carried out in vertical drums (diameter 300 mm and 437 mm, with heights of 1200 mm and 1450 mm) having inlet risers with drum diameter to riser diameter ratio of 3.75 and 6.0. Air-water mixture at atmospheric condition was used in those studies to measure entrainment. The water and air superficial velocities were maintained in a range covering the flow