



Air Water Loop for investigation of flow dynamics in a steam drum: Carryover experiments and CFD simulation

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ABSTRACT

Advanced Heavy Water Reactor (AHWR) being developed in India is a vertical pressure tube type boiling water reactor. In case of AHWR the steam-water two-phase flow from the core is separated in horizontal steam drums purely due to gravity i.e. density difference between the steam and water. This simple principle eliminates the need for mechanical separators and associated system pressure drop. However, the separation efficiency is affected by the entrainment phenomenon, i.e. conveyance of water droplets by the separated steam out of the drum i.e. carryover. Carryover estimation for new equipment with existing empirical correlations may not be reliable and experimental investigations in relevant geometries are necessary. In the present work carryover process has been investigated in a test facility known as Air-Water Loop (AWL). The facility aims at simulation of gravity separation of two-phase flows relevant to AHWR steam drum, using air-water mixture. During the experiments, carryover at operating levels closer to exit has been measured. AWL also has a facility for optical measurements using high speed camera. Measurements on droplet size distribution have been carried out with shadowgraph technique at different operating levels. The present work also involves the analysis of carryover using 3-D Euler-Lagrangian simulations with OpenFOAM based solver.

1. Introduction

Entrainment is observed in systems where liquid and gas phases are in relative motion. Carryover may be defined as pneumatic conveyance of drops of liquid into gaseous phase. Carryover phenomenon can be observed in process equipment such as industrial boilers, evaporators, distillation columns and also in case of nuclear reactors. Consider a scenario of a bubbling pool inside the process equipment, when a Vapor bubble arrives at the free surface it bursts out and Vapor leaves the surface. This bursting of bubble leads to formation of number of liquid droplets. These droplets may get carried along the bulk Vapor/gas flow depending on their initial momentum and magnitude of forces acting on them, primarily drag and buoyancy. The dissolved salts in liquid droplets may get deposited on equipment and piping walls and can cause mechanical damage/corrosion. In case of steam generators, carryover reduces the separation efficiency and also can cause severe damage in turbines. Therefore carryover is not desirable. The carryover depends on various factors such as size and velocity distribution and velocity of droplets, bulk velocity and flow pattern of the carrier phase and balance between forces acting on droplets such as gravity,

buoyancy and drag.

Advanced Heavy Water Reactor (AHWR) being designed in India is a vertical pressure tube type, boiling light water cooled and heavy water moderated nuclear reactor (Sinha and Kakodkar, 2006). The coolant flow in core is generated by two-phase natural circulation for the removal of heat generated in fuel rod bundle. Fig. 1 shows the schematic of Main Heat Transport System (MHTS) of AHWR.

The coolant flow through core is a result of balance between buoyancy and pressure drop in the MHTS loop. The two-phase boiling water from the core (1) of the reactor is transported to steam drum (2) situated 30 m above the reactor core, via tail pipes (3). The separated water returns to core via downcomer (4) and feeders (5). The steam drum is a horizontal pressure vessel with circular cross-section having 4 m in diameter and 11 m in length. There are total 452 fuel channels (6), 452 tail pipes and 452 feeders which are connected to 4 number of steam drums. Each steam drum receives flow from 113 tail pipes which are arranged symmetrically and are connected from sides at the bottom portion of drum. Vertical baffles are placed inside the drum to avoid mixing between two-phase flow entering the drum and the separated water in downcomer region. As steam leaves the drum and MHTS, equal

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Nomenclature

a	Distribution parameter in Eqs. (11) and (12)
C_D	Coefficient of drag
C_p	Heat capacity at constant pressure (J/kg K)
d	Droplet diameter (m)
d_{max}	Maximum droplet diameter (m)
e	Internal energy (J)
D	Diffusion coefficient (m ² /s)
D_H	Hydraulic diameter of vessel/equipment (m)
D_H^*	$= D_H / \sqrt{\sigma/g(\rho_f - \rho_g)}$ Non Dimensional Hydraulic diameter of vessel/equipment
E_{fg}	Entrainment fraction
F	Force (N)
g	Gravitational acceleration constant (m/s ²)
H	Enthalpy (J/kg)
h	Height from separation interface (m)
h^*	$= h / \sqrt{\sigma/g(\rho_f - \rho_g)}$ Non dimensional height from the separation interface
J	Mass diffusion flux (kg/m ² s)
J	Superficial velocity (m/s)
J^*	$= J / (\sigma g (\rho_f - \rho_g) / \rho_g^2)^{1/4}$ Non dimensional superficial velocity
K	Kinetic Energy
k	Turbulent Kinetic Energy
m	Mass (kg)
$N_{\mu g}$	$= \mu_g / \sqrt{\rho_g \sigma \sqrt{\sigma/g(\rho_f - \rho_g)}}$ Gas viscosity number
p	Pressure (N/m ²)
q	Heat flux (W/m ²)
R	Rate of production
S	Source Term
S_c	Schmidt Number $\mu/\rho D$

T	Temperature (°C)
t	Time (s)
U	Velocity (m/s)
$\mathbf{u}$	Velocity vector
V	Volume (m ³ /s)
Y	Mass fraction of species

Greek symbols

ρ	Density (kg/m ³)
σ	Surface tension (N/m)
μ	Dynamic viscosity (Ns/m ²)
η	Transformed variable as per Eq. (12)
ω	Vorticity
τ	Stress tensor
λ	Thermal conductivity (W/mK)

Subscripts

avg	Average
air	Air
c	Carrier phase
l	Liquid
g	Vapor/Gas
he	Heat exchange
i	Species
m	Mass
mo	Momentum
p	Particle phase
t	Turbulent

amount of mass of feed water is introduced in the drum. The normal

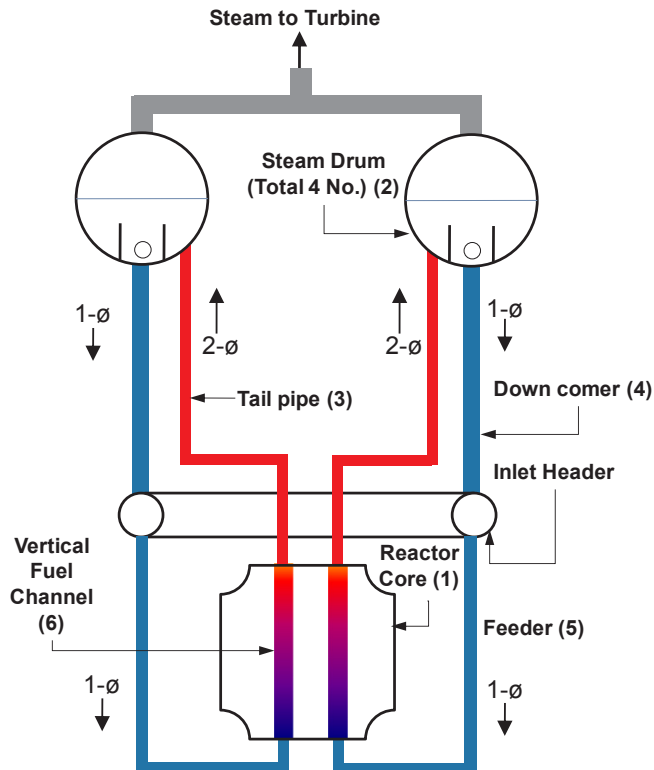


Fig. 1. Schematic of MHTS of AHWR.

operating level for 100% full power operation in steam drum is 2.2 m. The steam gets separated by gravity i.e. due to density difference between steam and water. No mechanical separator is used. The horizontal orientation of steam drum provides large area for steam-water separation.

Several researchers in the past have addressed the problem of quantification of entrainment/carryover (Cheng and Teller, 1961; Newitt and Dombrowski, 1954; Garner et al., 1954; Spiel, 1994; Aiba and Yamada, 1959; Rozen et al., 1970; Sterman, 1958; Kolkolostev, 1952). Various empirical correlations exist in literature; however these correlations are developed from experiments in simple geometries. Many of experiments are carried out in vertical cylindrical geometries of diameters 0.3 m (Garner et al., 1954; Aiba and Yamada, 1959). While practical equipment involves geometries with varying cross-sectional flow area and complex internals. Though the fundamental processes (bubble rupture and droplet conveyance) remain same, geometry specific effects are not addressed in the existing empirical correlations.

We have therefore, designed and constructed a test facility, Air-Water Loop (AWL) having a scaled down model of AHWR steam drum. It has a provision for visual observation of separation interface as the model is constructed with transparent windows. Since visual/optical studies are difficult for steam-water mixture at the rated operating conditions of 70 bar and 285 °C, the AWL operates with air-water mixture at atmospheric pressure and ambient temperature.

In the present paper a brief literature review on carryover phenomenon in a pool boiling scenario is presented followed by description of the test facility, and experimental work in detail. Analysis using 3-D Euler-Lagrangian simulation for experimental conditions has also been presented.

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