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Pattern recognition algorithm for analysis of chugging direct contact condensation

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A B S T R A C T

Direct contact condensation of steam bubbles in a boiling water reactor suppression pool has long been studied utilizing video recording of experiments. The use of video recording enables observation of the behaviour of the bubble surface area and can assist in validation of computational fluid dynamics models.

A direct contact condensation experiment of the suppression pool test facility PPOOLEX was recorded using high-speed cameras. The recorded video material was used for development of a pattern recognition and data analysis algorithm. 300 fps video of 48 s duration was cut into frames with a resolution of 768 px × 768 px. The side profile of the bubbles was identified and the volumes and surface areas of the bubbles were evaluated using a voxel-based method.

The purpose of the algorithm was to determine the shape and size of steam bubbles during their formation, expansion, collapse and re-formation. The most probabilistic chugging frequencies were estimated. The bubble geometry data were also used to determine the velocity and acceleration of the phase interface, as condensation induced Rayleigh-Taylor instability develops on the bubble surface during the bubble collapse, as the heavy phase accelerates towards the light phase. Knowledge of the critical wave length is necessary for mesh spacing in CFD calculations.

The algorithm appears to be promising. Some limitations exist and approximations need to be made due to the challenging video shooting conditions. The algorithm works well for cylindrical bubbles and provides important data on the dynamics of the phase interface necessary for numerical modelling of direct contact condensation.

1. Introduction

Direct contact condensation (DCC) of saturated steam in subcooled water can cause rapid pressure transients and accelerate the liquid to high velocity, leading to high dynamic loads on surrounding structures. These loads are encountered in many engineered systems e.g. in the form of instantaneous water hammer in pipes or as periodic condensation oscillations of submerged steam injections. DCC is, however, an essential phenomenon in certain nuclear engineering applications such as steam-driven water injection systems and suppression pools.

Liquid phase turbulence near the gas-liquid interface and available interfacial area determine the DCC heat transfer coefficient. DCC is controlled by the liquid heat on the liquid side and by surface pollutants such as non-condensable gases on the gas side. The conduction dominated boundary layer on the liquid side can be thin, and heat transfer from the interface is controlled mainly by turbulent convection, i.e., eddies. Thus, a valid liquid side heat transfer correlation is the most important part when modelling DCC in mildly sheared and lowly subcooled stratified flows. However, if the subcooling is high and the interface is wavy or unstable, as on a bubble in a liquid, the interfacial area modelling has increased importance in the heat transfer solution. This importance is not only due to the increased heat transfer area in such conditions, but also due to the interface motion, which is two-way coupled with the liquid side turbulent heat transfer mechanism. That is, a higher DCC heat transfer rate causes suction on the interface, reshaping it and increasing the interfacial area. Waviness and other interfacial instabilities play a significant role in determining the rate of interfacial area increase and the eddy size in the liquid side.

DCC of steam bubbles has long been an important research subject in study of boiling water reactor (BWR) suppression pools. In order to prevent pressure build-up, it can be essential to condense a large amount of steam rapidly, e.g., during a loss of coolant accident (LOCA) or safety relief valve operation. DCC is the most rapid and straightforward means to achieve rapid condensation. In BWR suppression pools, saturated steam is discharged through large submerged vent pipes into a deeply subcooled mass of water. In such a case, the condensation mass

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Nomenclature

Variables

$\mathbf{a}$	acceleration
A	surface area
d	size of a one pixel
d_i	number of nonzero elements of a row
f	frequency
Fs	frame rate
$\mathbf{F}$	face array
h_i	height
λ_c	critical wavelength
λ_m	predominant wavelength
M_i	number of pixels
n	image number
N	total number of images/cylinders
r_i	radius
$r_{i,s}$	vertices
ρ_l	density of liquid
ρ_v	density of vapour
S	patch area
σ	surface tension
t	time
$\mathbf{v}_i$	vertex vector
$\mathbf{v}$	velocity
V	volume
$\mathbf{V}$	vertex array
y	distance
$\lvert Y(f)\rvert$	absolute value of amplitude

Subscripts

i	index
l	liquid (water)
s	element
v	vapour (steam)

Abbreviations

BWR	boiling water reactor
CFD	computational fluid dynamics
DCC	direct contact condensation
FFT	fast Fourier transform
fps	frames per second
LOCA	loss of coolant accident
PACTEL	parallel channel test loop
PIV	particle image velocimetry
(P)POOLEX	condensation pool experiments
WMS	wire-mesh sensor

flow rate is high, and it is possible that the pressure decrease within the lighter phase causes interfacial accelerations higher than the acceleration of gravity. Interfacial accelerations of order of 100–1000 ms^{-2} magnitude have been observed in suppression pool cases (Patel et al., 2017). Such high accelerations invoke interfacial instabilities, i.e., Rayleigh-Taylor (Strutt, 1883; Taylor, 1950), Kelvin-Helmholz (Drazin, 2002) and Richtmyer-Meshkov (Richtmyer, 1960; Meshkov, 1969; Brouillette, 2002) instability, which cause roughening of the steam-water interface. Interface roughening increases heat transfer rate (Brennen, 2014), and thus also condensation heat transfer rate should increase temporarily. This recurrently increasing interfacial area together with high turbulence cause condensation oscillations and a phenomenon called chugging. In consequence, the steam injected to the pool causes high dynamic loads on the walls and internal structures. Due to the rapid movement of the phase interface, direct measurement of heat and mass transfer is impossible during chugging with existing

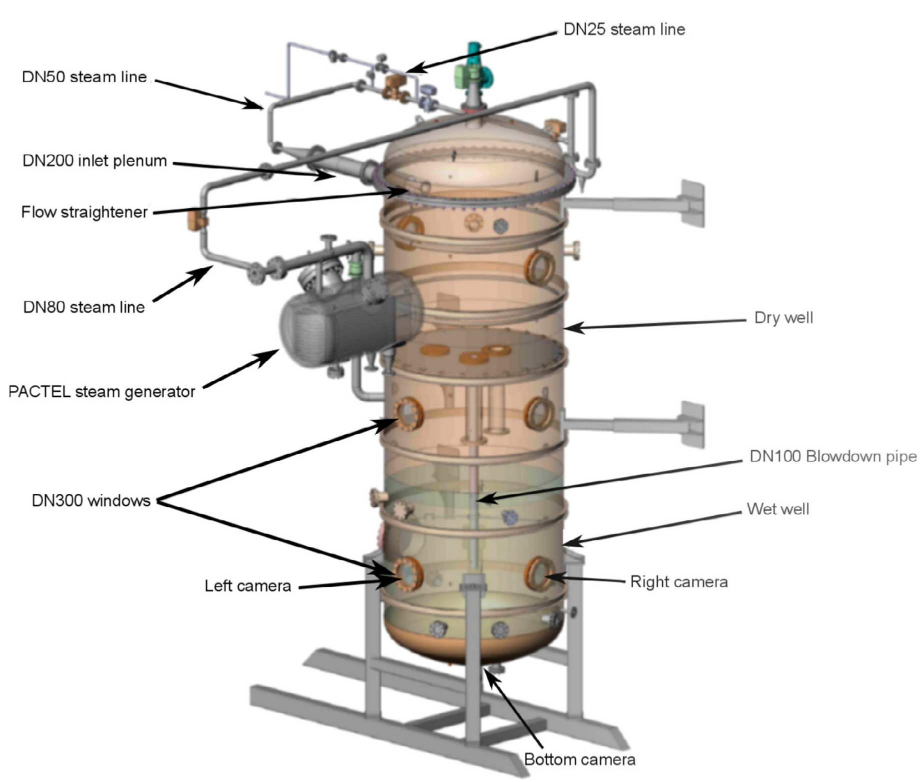

Fig. 1. PPOOLEX test facility. Locations of the high-speed cameras are also marked.