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Condensation induced water hammer: Numerical prediction

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ABSTRACT

Contact of steam and subcooled water in a pipe or a pressurized vessel leads to intensive condensation accompanied by a pressure drop in the volume of condensing steam and an acceleration of the surrounding water mass towards the steam volume, which can result in a severe water hammer and plant damage. This phenomenon is known as the condensation induced water hammer (CIWH). A one-fluid model is developed for the prediction of pressure surges during CIWH. It is shown that the reliable prediction of pressure surges strongly depends on the calculation of the condensation rate, transient friction and the water column–steam interface tracking. Due to the lack of the CIWH condensation models, a new approach is derived. The one-fluid model predictions of pressure surges are compared with available measured data from a CIWH experimental facility and acceptable agreements are obtained. In addition, the ability of the developed model to simulate the water cannon event, which takes place during the steam drainage into the pool of subcooled water, is demonstrated. Experimentally observed considerable scattering of test data under the same conditions is related to the condensation rate and its dependence on the entrained droplets–steam interfacial area concentration in the vicinity of the water column head.

1. Introduction

The condensation induced water hammer (CIWH) is a fast thermalhydraulic phenomenon that can cause a serious damage to equipment and endanger lives of working staff in all plants where vapor and subcooled liquid come into contact. Direct contact of subcooled liquid and vapor leads to intensive condensation. The vapor transition to liquid state results in a substantial fluid volume reduction, which causes a pressure drop in a part of the pipe filled with the condensing vapor. The pressure difference between parts of the pipe filled with liquid and vapor leads to a liquid column acceleration and its impact onto an obstacle, such as a valve, a closed end of the pipe or an another liquid column. A pressure pulse at the moment of the liquid column impact and a generated pressure wave propagation might have a potential for the damage of pipe walls, fittings, pipe hangers and vessels.

It was reported that CIWH occurred in various thermalhydraulic systems: in the feedwater system and the steam generator in the nuclear power plant (Serkiz, 1983; Beuthe, 1997), in the feedwater pump of the steam boiler in the thermal power plant (de Vries and Simon, 1985), in the district heating system (Kirsner, 1999) and in the ammonia refrigeration system (Martin, 2009). Previous experimental research has shown that pressure peaks of tens of bars or even higher than hundred bars can occur in pipes initially filled with subcooled water and steam at nearly atmospheric pressure. An impulse generated during a large steam bubble

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Nomenclature

A	area, m^2
a	thermal diffusivity, m^2/s
a_i	interfacial area concentration, m^2/m^3
c	sonic velocity, m/s
D	diameter, m
D_H	hydraulic diameter, m
f	friction coefficient
g	gravity constant, m/s^2
h	specific enthalpy, J/kg, heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(mK)
L	length, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
r	latent heat, J/kg
Re	Reynolds number
$\dot{q}$	heat flux, W/m^2
t	time, s
u	velocity, m/s
v	specific volume, m^3/kg
We$_{cr}$	critical Weber number
x	spatial coordinate, m
x_t	thermodynamic quality

Greek symbols

Γ_c	condensation rate, kg/(m^3 s)
ε	small distance, m
θ	pipe inclination, deg
ρ	density, kg/m^3
σ	surface tension, N/m
ν	kinematic viscosity, m^2/s

Subscripts

c	condensation
D	droplet
g	gas phase, steam
i	interface
l	liquid phase
res	reservoir
s	isentropic
sat	saturation
u	unsteady
0	initial time

Superscripts

$'$	saturated water
$''$	saturated steam

collapse in a vertical pipe between the lower stagnant hot water column and the upper downward accelerating column of cold water was investigated by Gruel et al. (1981). They observed the liquid column as a rigid body and derived a simple mechanical model for the prediction of the water column velocity and impulse at the moment of impact, as well as the resulting pressure peak. Zaltsgendler et al. (1996) investigated CIWH in a vertical pipe initially filled with steam and fed with cold water by a quick opening valve at the bottom. The performed experiments showed cases with great pressure pulses, from initial several bars to approximately 160 bar. These experimental conditions were simulated with the thermalhydraulic nuclear reactor safety code TUF by Liu et al. (1996). For this purpose the TUF code was upgraded with a model for the steam–water interfacial area concentration at the water column head. It was assumed that the interface between the water column and steam consists of certain number of bubbles on the water side and entrained droplets on the steam side, and such an interfacial area was kept constant during the water column movement.

Due to its importance for the safety of nuclear power plant steam generators and feedwater systems, investigations of CIWH in the countercurrent flow of subcooled water and steam in horizontal and slightly inclined pipes were performed by Bjorge and Griffith (1984) and Chun and Yu (2000). Recommendations were presented for the prevention of CIWH in such two-phase flow conditions. Also, CIWH caused by the cold water inflow into the horizontal pipe filled with steam was experimentally investigated and numerically simulated by Barna et al. (2010). The numerical simulations were performed with the WAHA3 code, which is based on the one-dimensional two-fluid model of transient steam–water flow. In this study CIWH was caused by rapid condensation of a steam bubble that is entrapped by slugs of subcooled water, which are formed due to the Kelvin–Helmholtz instability of the water layer in the stratified two-phase flow in the horizontal pipe. Another mechanism that leads to CIWH is the water cannon phenomenon. It can occur during the discharge of the steam turbine exhaust piping into a volume of cold water. Steam can be trapped in the pipe when the exhaust valve is closed. The steam and cold water contact leads to rapid condensation and subcooled water is being drawn into the tube. The formed water slug is stopped by the valve, resulting in a large pressure pulse. A simulation of the water cannon phenomenon by the thermalhydraulic nuclear reactor safety code RELAP5/MOD3 code was reported by Yeung et al. (1993).

Experimental investigations by Liu et al. (1996) and Barna et al. (2010) have shown a significant scattering of the experimental test data under the same experimental conditions. This scattering is attributed to a stochastic nature of the water column head disintegration. Namely, the condensation rate at the water column head, which governs the column acceleration and the subsequent pressure peak during CIWH, depends on the steam and water contact area. The information on this phenomenon is limited. There are available results of Seo and Bankoff (1988) who experimentally investigated the entrainment of water droplets from the accelerated water column head and condensation of steam onto the entrained droplets. They related the relative velocity between the entrained droplets and the water column head with the column

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