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A numerical analysis on the effect of inlet parameters for condensation induced water hammer

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HIGHLIGHTS

- Condensation induced water hammer phenomenon is analysed with RELAP5/Mod 3.4.
- Effect of various inlet conditions on the occurrence of CIWH are investigated.
- Pressure peak amplitude and location has strong dependency on water subcooling.
- Superheated steam does not have significant impact on pressure amplitude.
- Presence of dry saturated steam is the necessary condition for CIWH.

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ABSTRACT

Direct contact condensation (DCC) is almost an inevitable phenomenon during accidental condition for all LWRs. Rapid condensation caused by the direct contact of steam and subcooled water can lead to condensation induced water hammer (CIWH). The present work explores the underlying physics of CIWH phenomenon in a horizontal pipe under different inlet conditions such as inlet water temperature, pressure difference between steam and water section, steam superheating, steam quality and duration of valve opening using RELAP5/Mod 3.4. This work emphasises on the prediction of pressure peak magnitude in conjunction with its location of occurrence under different parametric conditions. The stratified to slug flow transition is presented in terms of the 'flow regime map' which is identified as the primary cause for pressure wave generation. The strongest pressure wave amplitude due to CIWH is found to be 116.6 bar for $\Delta P = 10$ bar. Observation reveals that peak pressure location shifts towards the subcooled water injection point for higher inlet water temperature. For the lowest inlet water temperature ($T_{in} = 20$ °C), the peak pressure is found at a distance of 47.5 cm away from the water inlet whereas, for the high water temperature ($T_{in} = 120$ °C), peak pressure is observed at 6.25 cm away from the injection point. It is also observed that the duration of valve opening significantly affects the location of peak pressure occurrence. This study also reveals that the presence of superheated or wet steam could possibly avoid the occurrence of CIWH.

1. Introduction

In water cooled nuclear reactor systems of all designs, direct contact between steam and subcooled water is almost inevitable during accidental scenario such as loss of coolant accident (LOCA) and loss of flow accident (LOFA). The direct contact between steam and subcooled water may cause an intense condensation at the interface between the two phases and result in a phenomenon which is often termed as condensation induced water hammer (CIWH). This CIWH phenomenon has got attention among the researchers as it has adequate potential to cause serious damage to reactor components (e.g. pressurizer, primary and secondary coolant loop, steam generator, containment pressure suppression pool etc.) which may have serious implications on plant integrity and safety.

The past studies reveal that the Griffith and co-workers conducted both experimental and analytical investigations in a systematic way to quantify the underlying mechanism regarding the

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Nomenclature

D	test section inner diameter, mm
L	test section length, m
P_{steam}	steam pressure, bar
P_{water}	water pressure, bar
T_{in}	inlet water temperature, °C
T_{liq}	local temperature of water, °C
T_{sat}	saturation temperature, °C
T_{steam}	local temperature of steam, °C
x	physical location, cm
Greek symbols	
α	void fraction
ΔP	pressure difference between steam and water section, bar
ΔT	temperature difference, °C
Δt	time step size, s
Δx	grid size, mm
Subscripts	
g	gas phase
sub	subcooling
sup	superheating

onset as well as the avoiding of CIWH phenomenon in a horizontal or nearly horizontal pipe. Bjorge and Griffith (1984) developed an analytical model to validate their experimental results and proposed an "absolute stability limit" in terms of "Taikel-Dukler" stability parameter to avoid the condensation driven water hammer in a counter current flow situation between steam and subcooled water in a pipe geometry. Swierzawski and Griffith (1990) developed a stability map using the "CHOP" program based on the work of Bjorge and Griffith (1984). Three different test conditions based on the mode of injection of subcooled water (e.g. downward and upward filling for vertical pipe and filling from one end for horizontal pipe) into the test section are carried out by Chou and Griffith (1990) both experimentally and analytically for the development of a CIWH avoiding algorithm. Griffith and Silva (1992) conducted an experimental work and proposed two conditions for avoiding the CIWH in terms of pipe inclination angle and condensate drainage velocity. Lee and Bankoff (1984) performed experiments with inclined pipes and developed stability maps indicating the effect of pipe inclination on the occurrence of water hammer. Chun and Yu (2000) conducted both the experimental and analytical studies on CIWH in a long horizontal pipe with countercurrent flow situation. The authors also developed the 'KAIST-CIWH' code along with a CIWH avoiding guide chart for specific combinations of different flow parameters. Schultz et al. (2013) carried out an experimental and analytical analysis on the identification of the conditions that will mitigate the possibility of CIWH in the partially filled horizontal piping system of ECCS. The authors claimed that the presence of a layer of saturated water sandwiched between subcooled water and saturated steam may cause a reduction in the occurrence of direct contact condensation induced water hammer.

Singh et al. (2010) carried out a study to analyse the condensation induced water hammer phenomena caused by steam-water interaction in an Integrated Test Loop (ITL) facility and captured the shock pulses, pressure, temperature, flow rate and fluid levels in the loop after the onset of water hammer. Safe practice of operating the loop without encountering the incidence of water hammer is also identified.

The objective of the experimental work on CIWH investigated by Urban and Schlüter (2014) is quite different. The authors performed about 185 experiments with different combinations of Froude numbers and degree of subcooling of inlet water and concluded that the nature of CIWH phenomenon is purely stochastic.

In comparison to the experimental work regarding CIWH, the numerical investigation on the same is a few. Barna et al. (2010a, b) and Barna and Ézsöl (2011) carried out both experimental and numerical work on CIWH. The authors performed experiments in the PMK-2 as well as in the ROSA test facility with the primary objective for measuring the amplitude and duration of transient pressure peak as an outcome of CIWH. The group also developed the six equation two-fluid model based WAHA3 code (capable of capturing shock waves) which is used for the validation of the experimental results. Tiselj and Štrubelj (2009) carried out numerical simulation of CIWH in a horizontal pipe geometry using the computational fluid dynamics tool NEPTUNE-CFD. The authors compared the simulation results (transient temperature and void fraction) with the specific experimental outcomes of the PMK-2 test facility to predict the flooding wave as well as the temperature increment of the water. Tiselj and Martin (2010) used the WAHA code to study the CIWH phenomenon for the experimental setup developed by Martin (2009). In their study, the authors made a comparison between the experimental results and the results obtained by the WAHA code for the pressure peak as an outcome of CIWH with a stratified flow condition between saturated ammonia gas and subcooled liquid ammonia in a horizontal pipe.

Milivojevic et al. (2014) focussed on the numerical prediction of CIWH phenomenon in a vertical pipe geometry filled with saturated steam. In the numerical model, the authors used 1-D homogeneous mixture model for mass, momentum and energy equations and solved using MOC approach. The inclusion of the transient friction model in the momentum equation is claimed as a novelty by the authors.

Literature review reveals that the investigation on CIWH based on the best estimate nuclear safety analysis code RELAP (Reactor Excursion and Leak Analysis Program), is quite limited. To assess the capability of RELAP5 for capturing different water hammer transients, Kaliatka et al. (2005) performed numerical simulations for the comparison with the experimental outcomes of CWHTF and AEKI PMK-2 test facility. They found that the amplitude of the first pressure peak due to rapid valve opening is well captured by RELAP5 in comparison with the outcomes of CWHTF test. However, the authors reported that RELAP5 could not capture the pressure peak during the CIWH event in PMK-2 test facility. Holmström and Lundin (2014) carried out numerical simulations using RELAP5 to capture the fast pressure transients during water hammer scenario due to sudden valve closure. The authors claimed that in RELAP5, equilibrium model overestimates the amplitude of transient pressure data whereas it underestimates for non-equilibrium model. They have also reported that the frequency of pressure peak is lower in non-equilibrium model compared to the equilibrium model. Melikhov et al. (2008) compared the experimental results of CIWH in the ITS test facility with the results obtained by the WAHA code as well as the RELAP5/MOD 3.2. They found that for the same time step size (corresponding Courant number = 0.8), the amplitude and the time of occurrence of the pressure peak obtained by both the numerical codes (WAHA and