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Analysis of film boiling heat transfer during fuel-coolant interaction

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ABSTRACT

In the paper the applicability of the heat transfer models for the typical fuel-water and fuel-sodium interaction conditions are analysed and discussed. The important differences of sodium properties compared with water require not just adequate modelling of the film boiling regime but also adequate modelling of the transition boiling regime.

The aim of the paper is to discuss the heat transfer modelling approaches applicable for the fuel-coolant interaction codes. First, the applicability of the adjusted Epstein-Hauser correlation for the film boiling modelling is analysed either comparing the correlation to the experiments with water or analysing the sodium properties. In the paper two modes of the film boiling regime are discussed. Indeed, experiments performed with the sub-cooled water have indicated an increase in the heat transfer between the stable and unstable mode. The numerical correction factors of the adjusted Epstein-Hauser correlation are proposed for the stable and unstable modes of the film boiling regime. Second, for the stable mode of the film boiling regime a modified Epstein-Hauser correlation is proposed to enable better general matching with the experimental data at significant sub-cooling. Next, for the unstable mode an alternative correlation is proposed and assessed. Finally, the empirical correlation for defining the transition from the film boiling regime towards the transition boiling regime is used to discuss the relevance of the unstable mode or transition boiling regime modelling in sodium. For sodium, additional experiments should be performed.

1. Introduction

Experimental and analytical activities related to the fuel-coolant interaction (FCI) phenomena are mostly performed in the frame of safety studies for light-water reactors [1–4]. The analytical activities are performed with the models developed with the focus on the water [5,6]. Several experiments were also dedicated to the integral investigations of the fuel-sodium interaction phenomena [7–10]. However, the applicability of the models for the fuel-sodium interaction must still be demonstrated.

The important differences of thermo-dynamical and transport properties of sodium compared with water lead to the necessity to investigate some particular phenomena. In contrast to water, where the heat is mainly transferred in the film boiling regime, in sodium, the heat is most probably importantly transferred in the transition boiling regime. Because a large sub-cooling of sodium is expected in the real reactor situations, the focus of modelling should be on the sub-cooled conditions. Such modelling is of potential interest also for the analyses of core debris re-flooding with the sub-cooled water.

The minimum film boiling (MFB) temperature is considered as the necessary surface temperature above which a vapour film exists between the hot surface and the liquid coolant. This regime is considered as the film boiling regime. Below the MFB temperature, where the heat transfer occurs in the transition boiling regime, the hydro-dynamical film instabilities result in the liquid-surface contacts. The MFB temperature is limited with the homogeneous nucleation (HN) temperature above which the liquid-surface contacts are physically impossible [11]. In some experiments with the sub-cooled water and the surface temperature above the HN temperature the heat transfer was higher than typically observed in the film boiling regime [12–16]. Thus, it seems that at such conditions hypothetically two modes of the film boiling regime could be considered and discussed using the vapour film destabilization (VFD) temperature as a criterion for the transition between the modes. If the surface temperature is above the VFD temperature the heat transfer occurs in the stable mode of the film boiling regime. Below the VFD temperature the heat transfer increases due to the presence of instabilities on the strongly

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Nomenclature

A	dimensionless surface super-heat parameter
B	dimensionless liquid sub-cooling parameter
C	numerical factor, proportionality factor
c_p	specific heat
D	diameter
Fr	Froud number
L	heat of vaporization
Nu	Nusselt number
p	pressure
Pr	Prandtl number
q	heat flux
Re	Reynolds number
T	temperature
v	velocity

Greek

β	ratio
λ	thermal conductivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density

Subscripts

adjEH	adjusted Epstein-Hauser correlation
cor	correlation
crt	critical
EH	Epstein-Hauser correlation
film	vapour film
HN	homogeneous nucleation
HTY	Honda-Takamatsu-Yamashiro
liq	liquid
MFB	minimum film boiling
MHF	minimum heat flux
modEH	modified Epstein-Hauser correlation
sat	saturated
sur	surface
uns	unstable
vap	vapour
wire	wire

Superscripts

crt	critical

Abbreviations

FCI	Fuel-Coolant Interaction
HN	Homogeneous Nucleation
MFB	Minimum Film Boiling
MHF	Minimum Heat Flux
VFD	Vapour Film Destabilization

reduced film thickness. The existence of the two modes is also discussed in [17].

For the transition boiling regime and for rather low reduced pressures an approximate heat transfer model based on the estimation of the time length of liquid-surface contact was developed [18]. However, at the current level of the understanding of the key FCI phenomena processes the interpolation approach to model the heat transfer between the maximal and minimal heat fluxes could be considered as sufficient for the FCI codes. Thus in the paper only the heat transfer modelling in the film boiling regime in conditions relevant for the FCI phenomena with water and sodium are analysed. In FCI the relative melt droplet-coolant velocities are between some m/s at the time of the continuous melt fragmentation and some tenths of m/s at the droplet's terminal conditions before the eventual explosion. The melt droplets size is in the range of some mm in the premixing phase till a tenth of mm in the explosion phase. Typical surface temperatures are in the range of more than 3000 K and the coolant bulk temperature. Initially the coolant could be saturated or sub-cooled and at pressures greater than 1 bar. For water few experiments were dedicated to the film boiling regime and were performed in relatively relevant conditions [12,17,19–22]. Those experiments were used to support different approaches to model the film boiling regime [20,22,23]. For sodium to the best knowledge of the authors only one experiment was dedicated to the pool film boiling heat transfer [24]. The experiment, where a tantalum sphere was submerged in the sub-cooled sodium, was performed at conditions not completely relevant for the FCI phenomena. In the most recent analysis the boundary layer theory was used to describe the experimental data within the order of magnitude [25]. To conclude, general lack of experimental data in relevant conditions promotes the use of theoretical or physically based empirical correlations for the heat transfer modelling in the FCI codes.

In the film boiling regime also the effect of radiation on the quenching of corium melt droplets in water must be considered [26]. Due to the presence of void in the mixing zone the radiative heat transfer models are needed for the premixing phase. Indeed, different radiative heat transfer models were developed and implemented into the FCI codes [5,23,27,28]. In the explosion phase the radiation contribution is an order of magnitude lower compared to the film boiling. In this paper the effect of radiation is not discussed.

The first objective of the paper is to analyse the experiments with water at highly sub-cooled conditions, as expected also in sodium, and forced convection conditions, as expected during FCI. The aim is to discuss the use of the Epstein-Hauser approach to model the stable and unstable mode of the film boiling regime [29]. The second objective is to analyse the transition from the film boiling regime towards the transition boiling regime. The aim is to discuss the relevance of the film boiling and transition boiling heat transfer modelling in sodium.

2. Film boiling regime

The film boiling heat transfer in water is well characterized [22]. The theoretical background of the Epstein-Hauser (EH) correlation makes it the preferred choice for the characterization of the film boiling heat transfer in the FCI codes [5,23]. Our aim is to analyse the FCI conditions using the EH approach.

2.1. Assessment methodology

Generally the heat transfer in the film boiling regime is determined as:

$$q = Nu_{cor}\frac{\lambda_{film}}{D}(T_{sur} - T_{sat}). \quad (1)$$

The EH correlation for the Nusselt number between the hot surface and the film-liquid interface is [29]: