G Model
FUSION-7767; No. of Pages 4
ARTICLE IN PRESS

Fusion Engineering and Design xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Computational thermal fluid dynamic analysis of Hypervapotron heat sink for high heat flux devices application

Phani Domalapally[a,*], Fabio Subba[b]

[a] Centrum výzkumu Řež, Řež, Czech Republic
[b] Politecnico di Torino, Torino, Italy

HIGHLIGHTS

- Rohsenow and Transition boiling models, as in STAR-CCM+ are tested and compared.
- Different Hypervapotron configurations are tested using the above boiling models.
- Simulations were conducted to preserve both quantitative and qualitative features.
- The tested boiling models show excellent quantitative features (relative error ~10%).
- Qualitatively Transition boiling model is superior to Rohsenow boiling model.

ARTICLE INFO

Article history:
Received 3 October 2014
Received in revised form 5 February 2015
Accepted 10 February 2015
Available online xxx

Keywords:
Subcooled boiling
CFD
Hypervapotron
High heat flux

ABSTRACT

In fusion devices, plasma is the environment in which light elements fuse producing energy. More than 20% of this power reaches the surface of plasma facing components (e.g. the divertor targets, first wall), where the heat flux local value can be several MW/m^2. In order to handle such heat fluxes several coolants are proposed such as water, helium and liquid metals along with different heat sink devices, such as Swirl tubes, Hypervapotrons, Jet cooling, Pin-fins, etc. Among these, Hypervapotron concept, operating in highly subcooled boiling regime with water as a coolant is considered as one of the potential candidates. In this paper, a Computational Fluid Dynamic (CFD) approach is used to analyze the boiling flow inside Hypervapotron channel using two different boiling models: Rohsenow boiling model and Transition boiling model, these models are available in the commercial CFD code STARCCM+, and uses Volume of Fluid approach for the multiphase flow analysis. They are benchmarked using experimental data obtained from experiments conducted at Joint European Torus, UK. The simulated results are then compared with each other and also with other simulated data available to test the quantitative, qualitative features of boiling models in modeling nucleate as well as hard boiling regimes.

1. Introduction

Thermal hydraulic analysis of heat sinks, which can be used in cooling of the high heat flux components of the fusion reactor, is one of the very important issues that need to be addressed, as the heat fluxes on these components are expected to be of the order of 1 to several MW/m^2 [1]. Out of the several coolants that are proposed water cooling is very advantageous and when operated in subcooled boiling regime, below Critical Heat Flux (CHF) limit, gives very high Heat Transfer Coefficient (HTC), with low velocities and pressures compared to the other coolants. There are several ways of increasing the CHF limit using different heat sink configurations such as swirl tapes, Hypervapotron, helical fins, Jet cooling, porous coating/medium, etc. [2]. Among these Hypervapotron is capable of handling heat fluxes in excess of 30 MW/m^2, and for an equivalent flow the Hypervapotron has higher CHF limit, and lower pressure drop compared to swirl tubes [2].

This paper deals with the computational thermal fluid dynamic analysis of Hypervapotron, where two different boiling models are compared: Rohsenow boiling model [3], with the capability to model both nucleate and film boiling regimes, which was previously tested on flat-channel geometry [4] and Transition boiling model [3], with the capability to model nucleate and transition boiling regimes, which is more general than the more popular Rohsenow boiling model [5]. These models are available in the commercial CFD code STARCCM+ [3], and use Volume of Fluid (VOF)

* Corresponding author. Tel.: +420 733302867.
E-mail address: P_Kumar.Domalapally@cvrez.cz (P. Domalapally).

http://dx.doi.org/10.1016/j.fusengdes.2015.02.017
0920-3796/

Please cite this article in press as: P. Domalapally, F. Subba, Computational thermal fluid dynamic analysis of Hypervapotron heat sink for high heat flux devices application, Fusion Eng. Des. (2015), http://dx.doi.org/10.1016/j.fusengdes.2015.02.017

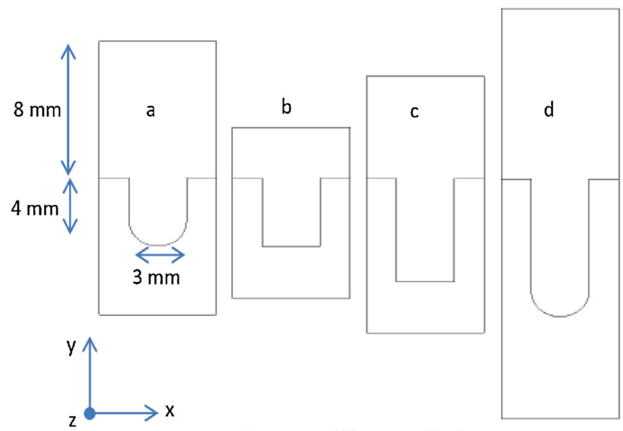

Fig. 1. Hypervapotron cross-sections for (a) Box scraper, (b) Div 4 × 3, (c) Div6 × 6 and (d) MkI respectively [6].

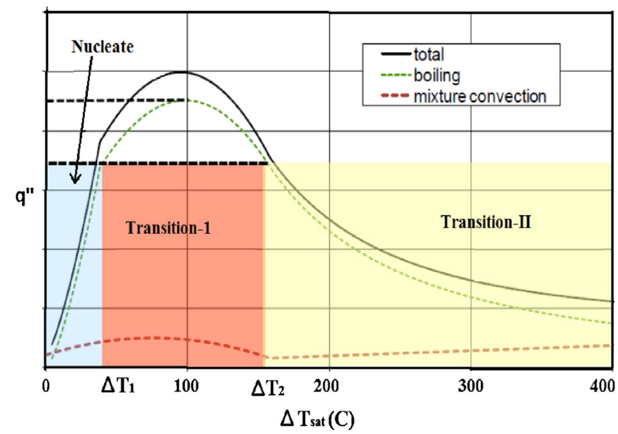

Fig. 3. Heat flux vs excess temperature [3].

approach for the multiphase flow analysis. The simulated results are then compared with the experimental data from JET [6]. Here the objective is to get simulated results closer to the experimental data by reducing the relative error (which is quantitative feature) and also to preserve the characteristic nature (qualitative features) of the experimental data.

2. Description

The increase in CHF value compared to smooth channel in Hypervapotron is obtained because of its fin design, where boiling and condensation occurs resulting in increased heat transfer capability [7]. Several experiments were performed on Hypervapotron geometry, to test its thermal hydraulic performance [7–10]. This work uses experiments performed by [8–10] as explained by Milnes [6,11], to perform the simulations, and then comparison is made with the experimental data and also with the simulated data by Milnes [6,11]. The experiments performed by the authors [8–10] have different cavity shapes and sizes, as shown in Fig. 1, and cover a wide range of heat fluxes and velocities. For more details about the experimental data the reader should refer to [6,8–11].

The typical experimental data can be divided into three parts/regimes as shown in Fig. 2, in the first regime where the slope of the curve is constant denotes single phase forced convection flow. As we increase the heat flux the slope of the curve decreases, which is due to increase in the HTC due to nucleate boiling or soft boiling. If we further increase the heat flux hard boiling region starts where we observe increase in slope due to more bubble formation and possibility of vapor blanketing, causing reduced HTC. The main problem associated with experimental data is related to the inlet and boundary conditions: only a limited data has all the boundary and inlet conditions specified.

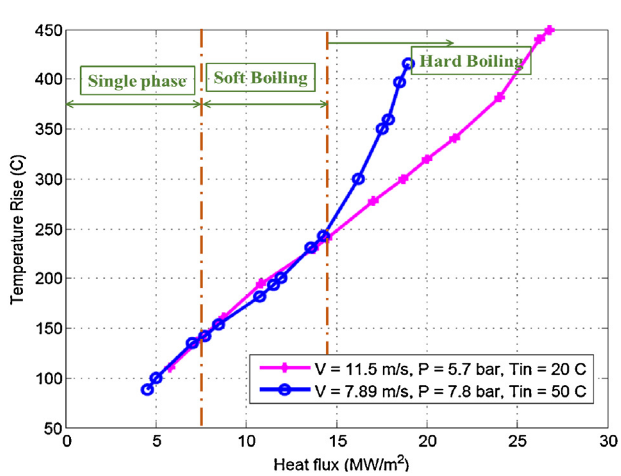

Fig. 2. Experimental data of Div 4 × 3 mm showing different boiling regimes.

It is very important to carry out the analysis of Hypervapotron using CFD, as CFD allows the analysis of fluid flow problems in detail, faster and earlier in the design cycle than possible with experiments. In the past several authors have tried to do the CFD analysis using different computer codes and boiling models [6,11–14], where the final results are mostly confined to the single phase and nucleate boiling regime, none of them try to elaborate the applicability of model beyond the nucleate boiling regime using their simulations. In this work two boiling models are used which show their applicability in modeling nucleate as well as hard boiling regime (regime 3 in Fig. 2). This paper only shows results of Div 4 × 3 and Box scrapper geometries (see Fig. 1), as these geometries from the experimental data point of view show better behavior.

3. Modeling strategy

In order to simulate the behavior of the heat sink under specified heat fluxes, the CFD tool should have models to cover the regimes as shown in Fig. 2 that is both single and two phase flow regimes. Not all the CFD tools have this capability. STARCCM+ [3], is one of the tool which is having this capability. Previously this tool was used to do the boiling analysis inside a flat channel [4], and the results show that the Rohsenow boiling model as in STARCCM+ is able to capture the physics with very low relative errors. In this work two boiling models are used to do the two phase flow analysis, the first one is Rohsenow boiling model and the second one is Transition boiling model as in STARCCM+. Both models use VOF technique to track the fluid–fluid interface. The details of the Rohsenow model are already explained in [4], here details of the Transition boiling model are given in brief. The nucleate boiling regime in the Transition model is more general than the Rohsenow model. This model adopts different correlation for the 3 regions shown in Fig. 3, trying to accurately capture the nucleate and the 2 transition regions.

Referring to Fig. 3, the correlations in the 3 regions are as follows:

$$q_{\text{boiling}}(\Delta T) = q_{\max} S\phi \left(\frac{\Delta T}{\Delta T_1}\right)^{k_1} \quad 0 \le \Delta T \le \Delta T_1 \tag{1}$$

$$q_{\text{boiling}}(\Delta T) = q_{\max} S \left(1 - 4(1-\phi)\left(\frac{\Delta T - \Delta T_{\max}}{\Delta T_2 - \Delta T_1}\right)^2\right)$$

$$\Delta T_1 \le \Delta T \le \Delta T_2 \tag{2}$$