CFD Simulations and experimental investigation of nucleate pool boiling of liquid nitrogen

Kenza Bouazaoui1*, Rachid Agounoun1, Imad Kadir1 and Khalid Sbai1

1Université Moulay Ismail (UMI), Laboratoire d'Etude des Matériaux Avancés et Applications (LEM2A), Ecole Supérieure de Technologie de Meknès, Km 5, route d'Agouray, N6, 50040, Morocco.

*Corresponding author: Email: k.bouazaoui@edu.umi.ac.ma

Abstract. Pool boiling heat transfer is a very efficient mode of heat transfer. It is used in various energy conversion and heat exchange systems and in the cooling of high energy density electronic components. In this work, heat transfer during nucleate boiling for a brass ribbon horizontally immersed in liquid nitrogen is experimentally and numerically studied. An experimental apparatus was built to conduct a pool boiling heat transfer study. The capabilities of Computational fluid dynamics (CFD) boiling model in pool boiling heat transfer is investigated. The computational model used combines the Euler/Euler two-phase flow. The general measurements of the super-heat, the influences of super-heat on the triggering of the boiling, as well as the critical flux which represents an important issue for the security of the systems were analyzed. The results of numerical simulations were compared with experimental data.

1. Introduction

Boiling heat transfer has always been a very interesting field of research because it is the most efficient way to remove the heat from a solid body with liquids and to reach the highest heat fluxes at the minimum wall superheat. Several studies [1, 2, 3] have focused on understanding fluid-solid combinations in order to obtain the highest heat fluxes with minimal superheating of the wall. Consequently, the process of boiling heat transfer has an important place in the industrial sector, particularly in the fields of electric power generation and refrigeration. Due to the complex physics of boiling phenomenon, it is studied intensively by experimental analyzes and the numerical simulations. In the first branch, several experimental studies are carried out to the process of heat transfer in boiling and which have proven to be effective on the analysis of the characteristics of boiling in transient state and in the stationary state [4-6].

The numerical simulations study of the boiling process also proven to be capable of reliably predicting phase-change (liquid/vapor) operation and heat transfer characteristics.

In recent years, Computational Fluid Dynamics (CFD) codes are considered to be the most promising numerical tools used for the analysis boiling heat transfer. Particularly, in the case of boiling flows, where heat is transferred into the fluid from a heated wall at such rates that boiling and vapor is generated.
Generally, most open-source CFD codes correspond to phase change are adapted to a multiphase Eulerian approach based on a two-fluid model. In the case of boiling heat transfer, where heat is transferred into the fluid from a heated wall, the multiphase CFD boiling models are usually coupled to appropriate wall boiling sub-models due to additional source terms describing the boiling physics at the heated wall that must be included in the equations [7]. Yi Liu et al [8] developed the CFD (Computational Fluid Dynamics) code to investigate the pool boiling of a cryogenic liquid. The model included the wall temperature effect on the vaporization velocity of the cryogenic liquid. The different boiling regimes (boiling nucleation, transition zone and boiling in film) were simulated by the use of a single model. The heat flux calculated for each boiling regime was compared with experimental data from the literature. This heat flux, which depends on the temperature difference between the wall and the cryogenic liquid, is different for each stage of boiling [9]. The CFD code was chosen to examine the complexity of the boiling phenomenon. In this sense, Tang et al [10] explored numerically the boiling mechanism of cryogenic fluids use of CFD model. Using a whole heating section, including boiling surface (polished with 5000# emery paper), which was immersed in LN2 pool, and the pool is inside a vacuum Dewar (with vacuum degree of the order of 10-4 Pa). The simulation focused on analysis the nucleate boiling process of the bubbles formation at the exit of the heated wall and the influences of super-heat on bubble departure diameters. The efficient cooling of the heating surface is limited by an important factor such as the critical flux (CHF). The latter appears when the relative rate between vapor and liquid reaches a critical value producing instability of the interface (Helmholtz instability) and preventing rewetting of the wall [11]. The security of the system is based on the determination of CHF. More different models developed for the prediction of maximum thermal flux and that are based on classical theories of critical flux [12, 13]. Recently, the most efficient determination of critical flux has been performed by numerical models well developed. For example, the numerical study of Lal et al focused on the prediction of CHF within the framework of Computational Fluid Dynamics (CFD) with an interface tracking (IT) method. In this paper, we present the simulation of nucleate heat boiling on a brass ribbon horizontally immersed in liquid nitrogen. The numerical simulation model proposed for this investigation is based on a CFD boiling model and the heat transfer model. The wall boiling model is developed in Euler-Euler multiphase frame work that solves transport equations for each phase. The model present in this paper is developed for analyzed the all boiling curve of LN2 pool boiling (natural convection area and nucleate boiling area) in atmospheric pressure.

2. Numerical model setup

Improving knowledge of the physical mechanisms governing boiling and the development of CFD have stimulated the construction of phenomenological models to study boiling heat transfer phenomena. These models can then be integrated into commercial calculation codes. In this section, the configuration of the boiling system, the basic equations and the equations of the boundary conditions used in COMSOL for numerical simulations are recalled. The main steps of a typical model are then presented.

2.1. Configuration of the boiling system

Figure 1. Shown the configuration of domain used in solver COMSOL multi-physics. The configuration is a 2D model, it is presents a heater element (brass ribbon) immersed in a container filled with liquid nitrogen (LN2). The immersed cell has very fine dimensions (length = 10⁻¹ m, width = 2.10⁻³ m, thickness = 50.10⁻⁶ m). The brass ribbon is heated by a heat flux density between q= 2.40 W/cm², q= 13.8 W/cm². The latter shows the heater surface for realizing the nucleate boiling phenomenon.
3. CFD model
In COMSOL multi-physics [15], the wall boiling models are developed in the context the multiphase Euler-Euler model. The CFD model used is based on a model contains the equations of motion (Navier–Stokes equations) and the equation of energy conservation.

![Figure 1. The computation domain of the boiling system, (1) Brass ribbon, (2) Liquid nitrogen, (3) Free surface](image)

Continuity equations:

\[
\frac{\partial \alpha_i \rho_i}{\partial t} + \nabla \cdot (\alpha_i \rho_i \mathbf{u}_i) = 0
\]

Transport equation for the volume fraction of the vapor phase:

\[
\frac{\partial \alpha_v \rho_v}{\partial t} + \nabla \cdot \alpha_v \rho_v \mathbf{u}_v = m_{i \rightarrow v}
\]

Where \( m_{i \rightarrow v} \) presented the mass transfer rate from liquid to vapor (kg/(m\(^3\)·s)). The subscripts “l” and “v” denote quantities related to the liquid phase and the vapor phase, respectively.

Momentum equation:

\[
\alpha \rho \frac{\partial \mathbf{u}}{\partial t} + \alpha \rho (\nabla \mathbf{u}) \mathbf{u} = \nabla \cdot \left[ p + \alpha \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \right] + \alpha \rho g + \mathbf{F}
\]

Energy equation:

\[
\rho \ C_p \frac{\partial T}{\partial t} + \rho \ C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q
\]

Energy equation for the heated wall:
In the wall, the heat transfer model uses the heat equation or heat conduction equation as the mathematical model for heat transfer in solid. The heat conduction equation is:

\[ \rho C_p \frac{\partial T}{\partial t} = \nabla (k \nabla T) \quad (5) \]

### 3.1. Boiling model

In the previous works [16, 17] of boiling heat transfer, it is possible to account the phase change model. The boiling heat transfer rate is necessarily related to the phase change rate, the mass transfer mainly controls the heat transfer. This mass transfer rate is typically depends on the interfacial area between liquid and vapor phases. The model takes care of the phase change near the wall as well as inside the domain. The mass transfer from liquid to vapor during evaporation is described as following [29]:

\[ m_{l-v} = C \rho_l \frac{T - T_{sat}}{T_{sat}} \quad T > T_{sat} \quad (6) \]

Where C is the mass transfer intensity factor or relaxation time (s\(^{-1}\)) in the vapor-liquid phase change [18].

The following table summarizes the input parameters used in the numerical model developed.

| Table 1. Thermal properties of the materials |
|---------------------------------------------|
| Material properties | Brass | Nitrogen | Unit |
| Density (\(\rho\)) | 8386 | 808.4 | kg.m\(^{-3}\) |
| Heat capacity (\(C_p\)) | 377 | 1040 | J.kg\(^{-1}\).k\(^{-1}\) |
| Thermal conductivity | 121 | 145.10\(^{-3}\) | w.m\(^{-1}\).k\(^{-1}\) |
| Specific heat ratio (\(\gamma\)) | 1.3967 | 2.07 | 1 |
| Dynamic viscosity (\(\mu\)) | - | 5.435.10\(^{-6}\) | Pa.s |

### 4. Experimental setup

#### 4.1. Description

To validate the numerical results, an experimental study was performed. The experimental device is composed of brass ribbon, power supply system, Dewar tank of liquid nitrogen (LN2), nitrogen liquid, and data acquisition system, as shown in Fig.2. The brass ribbon is immersed permanently in a Dewar tank filled with liquid nitrogen (LN2). Furthermore, a platinum probe Pt-100 used for measured the
fluid temperature in boiling vessel. Finally, a camera for the observation of boiling complete the device. The experiments are performed under atmospheric pressure (1 atm).

In our experiment study the variation of heat flux density \( q \) versus superheat \( \Delta T \) (boiling curve) is determined from the heat flux density and the wall superheat. The accuracy on the determination of the temperature and flux density is 0.3 K and 0.1 W/cm\(^2\), respectively.

The heat flux dissipated by Joule effect and the average ribbon superheat \( \Delta T \) are determined as follows:

\[
\dot{q} = \frac{U_{\text{ribbon}} \cdot I_{\text{in}}}{S_e} \tag{7}
\]

\[
\Delta T = T - T_{\text{LN2}} \tag{8}
\]

\( T \) presents the wall temperature; this temperature is determined by the electrical resistivity \( \rho \) Eq.9

\[
\rho(T) = \frac{R_{\text{s}}}{L_{\text{s}}} = \frac{U_{\text{s}}}{I_{\text{l}}} = \rho_0 (1 + \sigma_0 T) \tag{9}
\]

Figure 2. Experimental setup composed of container of liquid nitrogen (LN2), brass ribbon, acquisition system and power supply system.

5. Result and discussion

5.1. Simulation result

After the monophasic exchange phase (natural convection phase), boiling is produced when the element heater temperature reaches a maximum.

Fig. 3 shows the numerical results for the volume fraction distribution of vapor at nucleate boiling in the heater element surface (brass ribbons). A typical burst of small masses of vapor has been presented at the ribbon level. The existence of vapor on the surface has just explained the effect of heater wall on the liquid nitrogen evaporation. Indeed, when the wall is heated, a heat quantity transmitted by the heating element surface to the liquid, which is the liquid nitrogen near the heated wall, changed its liquid state to a set of vapor bubbles on the area. More particularly, the heat quantity generated by the
heating element surface in the boiling liquid increases with the increase of the wall temperature. This is confirmed by the Nukiyama study [19] with a metal surface immersed in water as a coolant. The small bubbles of vapor appeared on the heated surface in isolation for a medium heat flux density. The increase in the imposed heat flux density allows to increase the quantity of vapor on the heated surface.

5.2. Boiling curve

Figure 4 shows the results obtained in steady state regime of a brass ribbon mounted in horizontal position and immersed in a Dewar tank filled with liquid nitrogen (LN2). The manipulations and simulations allowing us to find the boiling curve (Nukiyama curve[11,19]). They highlight 3 zones: the natural convection regime, the nucleate boiling regime and the film boiling regime. The pure conduction regime can not be visualized because this regime exists for very small imposed flux density values.

The boiling curve of LN2 is begins by a natural convection area for low flux density. In this area, vapor has not occurred on the surface. The bubbles begin to appear for an average flux density of 1.2 W/cm² and a superheat of 11.3 K. The increase in imposed flux density makes it possible to increase the number of bubbles or the quantity of vapor on the heating surface.

When the flux density is imposed, it corresponds to the limit value of flux density (critical heat flux CHF) that can be exchanged without abrupt rise in the heating element temperature and risk of deterioration. The CHF or maximum flux is approached at an average flux density of 16.2W/cm² and a superheat of 11.2 K.

The simulated boiling curve is also presented in Fig.4. The experiment boiling curve between heat flux and super-heat for LN2 is used for comparison to evaluate our CFD simulations. Similarly, we note...
that the low heat flux between 0.30 W/cm² and 1.2 W/cm² corresponding to natural convection regime. As the heat flux increases, the super-heat increases accordingly during the nucleate boiling process. In this regime, superheat in around 7.86 to 10.52 K, and the applied heat flux ranges from 4.77 to 16.2 W/cm². The vapor emerged from the solid surface are clear. Simulated values were compared with the experimental results with a maximum error of 2.7% for pool boiling conditions investigated in this work.

6. Conclusion
In this paper, the LN2 boiling curve between heat flux and super-heat for experiment and CFD simulation study is presented and analysed. CFD formulations based on Euler-Euler multiphase model and the heat transfer model was built up. The simulations are performed in COMSOL Multiphysics software. The brass ribbon is used for the heating element. The liquid nitrogen is chosen as the working fluid due to its distinctive properties in hot wall cooling. Simulations were mainly realized for different heat fluxes applied and under atmospheric conditions. The results show the boiling curve regimes (natural convection regime and nucleate boiling regime) corresponding to low and high values of heat flux applied. The numerical simulation between heat flux and super-heat for LN2 pool boiling were in good accordance with the measured data.

![Figure 4. LN2 pool boiling curve: Experimental data and CFD simulation results.](image)

References
[1] Zhang B J, Kim K J, 2014, Nucleate pool boiling heat transfer augmentation on hydrophobic self-assembly mono-layered alumina nano-porous surfaces, *Int. J. Heat Mass Transf*, Vol. 73 p 551-561.
[2] Xu P, Li, Xua Y, 2015 Enhanced boiling heat transfer on composite porous surface, *Int. J. Heat Mass Transf*, Vol. 80 p 107 114.
[3] Sanna A, Hutter C, Kenning D B R, Karayannis T G, Sefiane K and Nelson R A, 2014 Numerical investigation of nucleate boiling heat transfer on thin substrates, *Int. J. Heat Mass Transf*, Vol. 76 p 45-64.
[4] Héas S, Launay S, Raynaud and Lallemand M, 1998, Transient nucleate boiling heat transfer from a thick flat sample. Proceedings of the second International Symposium on Two-Phase Flow modeling and experimentation, *Pise, Ed: E.T.S*, Vol. 1, p 205-210.
[5] Drach V, Fricke J, 1996, Transient heat transfer from smooth surfaces into liquid nitrogen. *Cryogénies, Vol. 36*, p. 263-269.

[6] Duluc M C, Francois X, 1998, Steady-state transition boiling on thin wires in liquid nitrogen. The role of Taylor wavelength, *Cryogenics Vol. 38* p 631-638.

[7] Kurul N, Podowski M Z, 1990, Multidimensional effects in forced convection subcooled boiling, *Proc. of the 9th International Heat Transfer Conference*, Jerusalem, Isral.

[8] Liu Y, Olewski T, Vechot L, Gao X, Mannan S, 2015, Modeling of a cryogenic liquid pool boiling by CFD simulation, *Journal of Loss Prevention in the Process Industries Vol. 35*, p.125-134  doi:10.1016/j.jlp.2015.04.006.

[9] Barron R F, 1999, *Cryogenic Heat Transfer*. Taylor & Francis, Philadelphia, USA.

[10] Xiaobin Z, Wei X, Jianye C, Yuchen W and Tang K, 2015, CFD simulations and experimental verification on nucleate pool boiling of liquid nitrogen, *Physics Procedia Vol. 67*, p 569 – 575, doi:10.1016/j.phpro.2015.06.077

[11] Lallemand M, 1991, Ebullition en vase. Entropie, N° 160, *Universités à l’Institut National des Sciences Appliquées de Lyon*, BE 8 235, p. 4-19.

[12] Zuber N, Hydrodynamic aspects of boiling heat transfer. *PhD. Thesis, University of California*, Los Angeles, CA, USA (also published as USAEC. doi 10.2172/4175511.

[13] Haramura Y, Katto Y 1983, A new hydrodynamic model of critical heat flux, applicable widely to both pool and forced convection boiling on submerged bodies in saturated liquids. *Int. J. Heat Mass Transfer, Vol. 26*, N° 3, p.389-399.doi:10.1016/0017-9310(83)90043-1

[14] COMSOL Multiphysics, COMSOL 4.3a, May 2012 http://www.comsol.com.

[15] Punekar H, Das S 2013, Numerical Simulation Jacket of Subcooled Nucleate Boiling in Cooling, *IC Engine, SAE International*, doi:10.4271/2013-01-1651.

[16] Liub J, Wanga G, Zhang a L, Y.Shia, Zhangb H andYao S 2017, Numerical simulation of single bubble boiling behavior, *Propulsion and Power Research* 6(2), p 117–125.

[17] Tian Y, Zhang K, Wang N, Cui Z and Cheng L 2017, Numerical study of pool boiling heat transfer in a large-scale confined space, *Appl. Therm. Eng* 118, p 188–198.

[18] Nukiyama S 1966, The maximum and minimum values of the heat Q transmitted from metal to boiling water under atmospheric pressure, *Int. J. Heat Mass Transf. Vol. 9*, p1419–1433.