CHAPTER 1

INTRODUCTION

Boiling heat transfer is the process in which phase change of liquid to vapour occurs. The phenomenon is characterized by high heat transfer capacity and low wall temperature, an essential requirement for industrial cooling applications such as nuclear reactors, two-phase heat exchangers and fossil fuel boilers. In comparison to those single-phase cooling solutions, boiling provides high heat transfer capacity through the latent heat of vaporization rather than single phase heat transfer. Besides, boiling can maintain the heated surface at a relatively low temperature and avoid system failure. Due to its importance in industry, much research have been extensively conducted to study the boiling heat transfer phenomena.

1.1 Theoretical Background

Boiling heat transfer has a wide field of applications: from simplistic cooking methods in daily life to high-tech multi-phase solutions for the chemical industry, power generation, spacecraft thermal management and cooling applications. Heat dissipation from integrated circuit chips require advanced cooling technologies. Micro heat exchangers have become one of the most effective cooling techniques for high-power density, compact applications [1]. They are used in high-speed processor chips, microprocessors, high-powered lasers, cutting-edge power and switching devices, and lightweight cooling applications like satellites, avionics, and portable computers [2]. Boiling heat transfer enhancement is necessary to achieve reduced energy consumption so that these industrial applications become more energy efficient. Boiling as a liquid-vapour phase change process is found to be a potential candidate for heat dissipation. Due to increasing energy density in heat transfer device, boiling heat transfer has been intensively studied in the past as well as now in many groups all over the world. The demand to transfer higher heat fluxes at the same or even at lower wall superheats is growing and makes the scientific investigation of boiling phenomena inevitable. Increment in heat transfer associated with boiling can offer a solution for enhancing heat transfer performance.

For engineering designs, nucleate boiling is the most important and desirable regime because high heat flux can be achieved with relatively low temperature excess. The critical heat flux (CHF) is an important and sensitive issue in boiling heat transfer. The CHF is also known as burnout heat flux, dry out or boiling crisis depending on the thermal phenomenon. Therefore critical heat flux becomes important in the design of equipment employing boiling heat transfer, deciding the upper limit of safe operation. After this limit, the temperature of the heating surface increases significantly and can lead to system failure.

Apart from the idea of optimising the cooling devices designs, enhancing the heat transfer capacity of the fluid itself is also a method to achieve higher heat dissipation ability. The inherent limitation of liquid thermal conductivity can be largely extended by adding metal and metal oxides particles, the thermal conductivities of which are higher than the liquids. Comparison of thermal conductivity of common liquids, polymers and solids has been shown in Fig. 1.1. Heat transfer fluids containing suspended particles of micro/millimeter sizes have numerous drawbacks like sedimentation, erosion, increased pressure drop, fouling etc. Advancements in material science have made it possible to produce nanometer-size particles that can overcome such problems. This is where nanofluids play a key role to enhance heat transfer performance as compared to pure liquids.

The main reasons that contributed to this enhancement of heat transfer performance in nanofluids are [3]:

a) The suspended nanoparticles increase the surface area for heat transfer and the heat capacity of the fluid.

b) The suspended nanoparticles increase the effective thermal conductivity of the fluid.

c) The interaction and collision among particles, fluid and the flow passage surface are intensified.

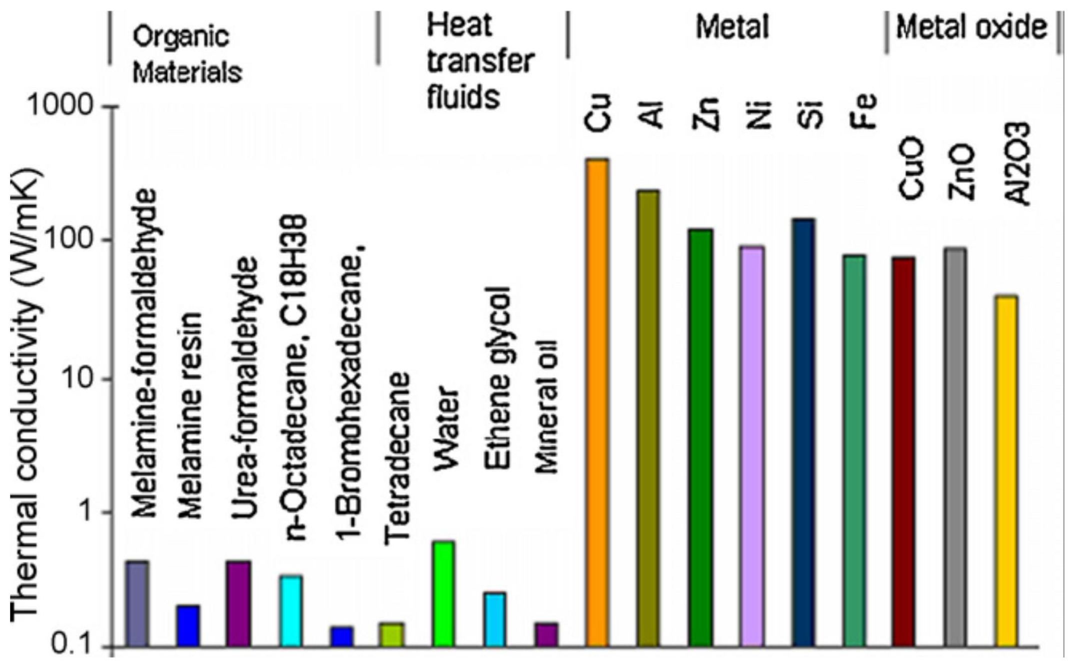

Fig. 1.1 Comparison of thermal conductivity of common liquids, polymers and solids [4]

Advanced technologies and new generation fluids with the capability to enhance flow and thermal characteristics are of critical importance now a days. Nanofluids are colloids made of a base fluid and nanoparticles that can significantly improve the heat transfer. Typical particle materials include oxides (TiO_2, Al_2O_3, ZrO_2, CuO, Fe_2O_3 and SiO_2 etc.), electrochemically noble metals (Cu and Ag etc.) and some other compounds (SiC, Carbon nanotubes etc.). The base fluids usually include water, ethylene glycol, propylene glycol, engine oil etc. In recent years, the rapidly advanced nanotechnology has spawned into many new engineering applications by implementing nanofluids, such as nuclear reactors [5], ultrafast cooling systems [6], solar collectors [7], microelectronics [8] and automotive industries [9] (Fig. 1.2). Nanofluids have been treated as perfect substitutions for pure liquids as energy transfer media, due to their merits in heat transfer capabilities, such as thermo-physical properties, enhanced single-phase convective heat transfer, and nucleate boiling heat transfer. Beyond that, the high surface to volume ratio, low mass, and low inertia of nanoparticles enable nanofluids to be highly colloidal stable and impact less erosion to thermal systems.

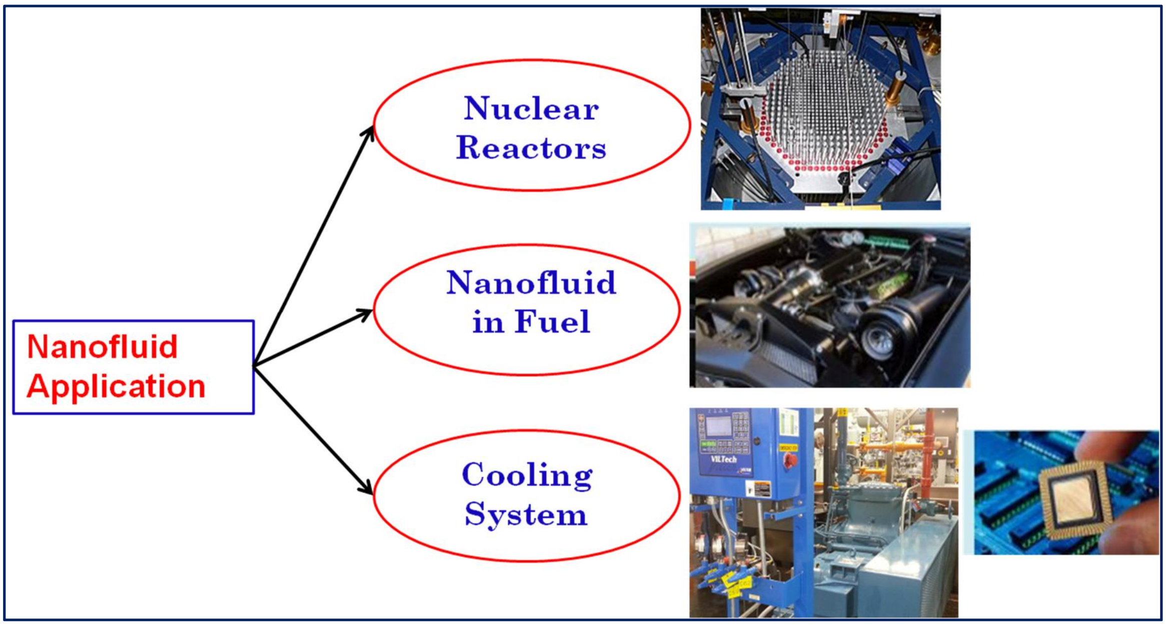

Fig. 1.2 Application of nanofluids

Literature shows, with the addition of nanoparticles, the thermal properties of a fluid are significantly modified. These in turn modify heat transfer and boiling phenomena. Much research have been conducted regarding nucleate boiling and critical heat flux of nanofluids. However, controversial results regarding enhancement or deterioration of the heat transfer during boiling have been published. Currently, it is not known how nanoparticles interact with bubbles originated during boiling and possibly reduce or enhance the heat transfer that occurs. Hence, detailed analysis of heat transfer mechanism and the bubble growth dynamics in nanofluid flow boiling is required.

1.2 Motivation

High-performance cooling systems are required for nuclear reactor cooling. In case of a loss of coolant accident (LOCA) in a nuclear reactor, Buongiorno et al. [5] suggested to use nanofluid into the in-vessel retention (IVR) to enhance the CHF, which could avoid the subsequent fatal nuclear accident.

Nanofluids can be introduced into a wide range of applications. The nanofluid can be introduced into the passive coolant systems (PCSs) in either the isolation condenser system (ICS) or the passive containment cooling system (PCCS) in boiling water reactor (BWR). Here, increasing the boiling heat transfer could significantly improve the safety margin. The nanofluids are considered as next generation heat transfer fluids because they present improved heat transfer properties as compared to pure liquids. The large surface area-to-volume ratio of the nanoparticles helps to enhance the stability of the suspensions. Very low concentration of nanofluids can continuously maintain the steady-suspension-state for a long time without causing serious sedimentation. Because of the nano-sized particles, fouling and erosion are substantially reduced with use of nanofluids. Keeping an eye on these appealing advantages, nanofluids draw increasing attention of the researchers.

Visualization of flow patterns could essentially help in understanding the heat transfer in nanofluid flow boiling because of the multi-phase flow [10]. Experimental methods using high-speed visualization and image processing have been highly recommended to study the phenomenon of bubble formation, growth and condensation due to its non-intrusiveness [11]. Several researchers experimentally investigated bubble behavior during sub-cooled flow boiling of water using high speed visualization [12-13]. So far the researchers conducted experimental and theoretical studies concerning boiling heat transfer and CHF under pool boiling and flow boiling conditions using nanofluids [14-17]. *However studies regarding flow pattern evolution in a vertical channel with a concentric heater similar to a single nuclear pin using nanofluids are rather scarce.* Visualization of flow patterns could provide better insight to the heat transfer mechanism in vertical channels. The change in flow pattern during flow boiling process due to the bubble fusion and varying void fraction in flowing fluid can lead to the change of flow boiling heat transfer condition. The flow boiling heat transfer in nanofluids is more complex than that in the water. The nanoparticle in the boiling nanofluids will produce effects on bubble generation, growth and departure. Therefore, the nanofluids flow boiling heat transfer coefficient and CHF may be different from that of base fluids because of the collective effect of suspended nanoparticles. So far, the research of nanofluids boiling heat transfer is less and limited. No research about the nanofluids boiling heat transfer characteristics from the viewpoint of bubble behavior has been reported.

1.3 Objective

The exploratory work has been conducted to emphasize the parameters which influence the boiling performance of nanofluids. It aims to study the feasibility and performance enhancement of nanofluid-cooled system as well as to characterize the heat transfer behavior of nanofluids. It is an effort to advance the research towards thermal management of cooling of nuclear reactors. The present research aims at conducting a systematic study of single-phase convective heat transfer and multi-phase flow boiling heat transfer of dilute oxide based nanofluids in a vertical channel.

After extensive literature survey, well-characterized heat transfer experiments have been performed in uniformly heated, single, circular, vertical channel to investigate the parametric effects on the heat transfer characteristics of single-phase convection as well as subcooled flow boiling. The effects of particle concentration, mass flux, heat flux, and inlet subcooling on the heat transfer coefficient have been studied in detail. Furthermore, flow visualization experiments have been carried out to have a clear picture of two-phase flow behavior and the boiling heat transfer characteristics of nanofluids. Experimental results are analyzed, discussed and compared against results from similar investigations.

1.4 Thesis Outline

The present chapter contains the background and motivation for the thesis and outlines the objectives of the research and the methods used.

Chapter 2 reviews the fundamentals of boiling, two-phase flow patterns and boiling heat transfer. An extensive review on flow boiling heat transfer and bubble dynamics of nanofluids is presented in this chapter. Chapter 3 describes the preparation of nanofluids as well as the characterization of nanofluids. Experimental characterization of effective thermo-physical properties of nanofluids have been presented in this chapter.

Chapter 4 describes the experimental facility, data reduction and experimental uncertainties. The instrumentation for high speed imaging has been presented and the procedure for conducting experiments has been discussed. Chapter 5 shows the heat transfer results from the subcooled flow boiling experiments with water and nanofluids. The effects of heat flux, mass flux and inlet subcooling on boiling incipience and subcooled boiling heat transfer have been explored. Results are shown in the form of boiling curves and heat transfer coefficients of water and nanofluids have been compared at varying mass flux and inlet subcooling. Delay in DNB in case of nanofluids has been discussed with reference to boiling curves.

Chapter 6 presents results from the two-phase flow visualization investigation. Bubble dynamics (nucleation, growth and detachment) in water and nanofluids has been discussed with the aid of high speed photography. Bubble departure characteristics of water and nanofluids have been compared. Flow pattern transitions of water and nanofluid have been compared and effect of nanoparticles on flow pattern transition has been studied.

The thesis is summed up in Chapter 7 under conclusions and future scope. Valuable experiences gained as a result of the work done for this thesis have also been discussed.