Sonneting Critical Heat Flux: Unexplored science in boiling flows

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Abstract

In water-cooled reactors, the operating heat flux is limited by phenomena known as critical heat flux (CHF). Even though CHF phenomena have been extensively investigated in the past, the flow physics at low pressure and low flow conditions (important during accidental conditions of LWRs and start-up of Natural Circulation Boiling Water Reactors (NCBWRs)) are not understood. To clarify the physics of CHF at such conditions, we have carried out a series of experiments. We found that at CHF, the classical bubbly flow changed to slug/churn flow due to an increase in bubble coalescence. With time, this flow pattern was found to change to an unusual reverse annular flow leading to an increase in the heater surface temperature, as the water did not come in contact with the heater surface. However, this new flow pattern could not sustain and was found to break down, allowing the liquid to touch the heater surface, resulting in quenching of the heater surface.The quenching heat removal rate was found to be significantly higher than the steady-state heat removal rate. Shortly after the quenching, the flow pattern was found to revert to bubbly flow again, and the phenomena repeated rhythmically with the wall temperatures continuously rising and falling in every cycle till the heater trip-setpoint was reached. We coined this interesting phenomenon as "Sonneting CHF". Interestingly, at CHF, unprecedented quenching scenarios were found to occur even though the heater surface temperatures were substantially higher.

Keywords: Sonneting critical heat flux, Subcooled flow boiling, Boiling crisis, Low pressure and low flow conditions

Introduction

Boiling is a common phenomenon in every household. Our ancestors started using the boiling process for cooking even before the invention of pottery via the quenching process, where stones were heated and dropped directly into water[1]. Owing to its ubiquitous nature, it comes as no surprise that every person has some degree of experience with the boiling process and steam production. In the 1700s, steam engines played a prominent role in the industrial revolution. However, it was not until the late 1800s, when the boiling process made its inroads into power industries where steam production started in conventional boilers. Most of the present generation's power industries rely upon steam to run turbines. In addition to steam production, some degree of the boiling process is generally used in many systems because of its good heat transfer characteristics. With a small temperature difference between the hot surface and cooling medium, excellent heat transfer can be achieved during boiling. It is not an understatement to say that boiling is the single most widely used process that runs the 21st century. The rate at which steam is produced is directly proportional to the heat input. Engineers aim to maximize the steam output for a given system.

In 1934, Nukiyama[2] was working on a project to maximize steam production. He conducted experiments on an electrically heated metallic wire immersed in a pool of water at 100°C. He observed that the wire burned even in the presence of water! This mysterious phenomenon is known as boiling crisis or critical heat flux (CHF).In day-to-day appliances, it is ensured that heat input is not so high as to cause damage. This is because beyond a certain heat input, the heat transfer can deteriorate siginificantly. Generally, the heat transfer from the surface to the cooling medium is measured in terms of heat transfer per unit surface area, also known as heat flux. The limited heat flux beyond which the heat transfer deteriorates is known as CHF. It is a practical limit on the maximum heat transferrable; it depends on various operating conditions, like flow, pressure, temperature, etc. Hence, CHF knowledge is essential to design systems that utilize the boiling process to its fullest potential for heat transfer and steam production. However, in the absence of CHF data, engineers design systems that operate at low heat fluxes to avoid system failure. Such a design is said to be conservative. Conservative designs are neither economical nor efficient. It is important to note that CHF is a design safety limit in nuclear reactors. A majority of the research is dedicated to ensuring adequate margins against CHF.

Classically, flow boiling CHF is broadly classified into two categories depending on the flow conditions: Departure from Nucleate Boiling (DNB) and liquid film dryout. Over the years, many experiments were performed at various operating conditions to understand boiling limits[3]. Usually, during DNB, the bubbles crowd near the heater surface and prevent the liquid from touching the surface, reducing

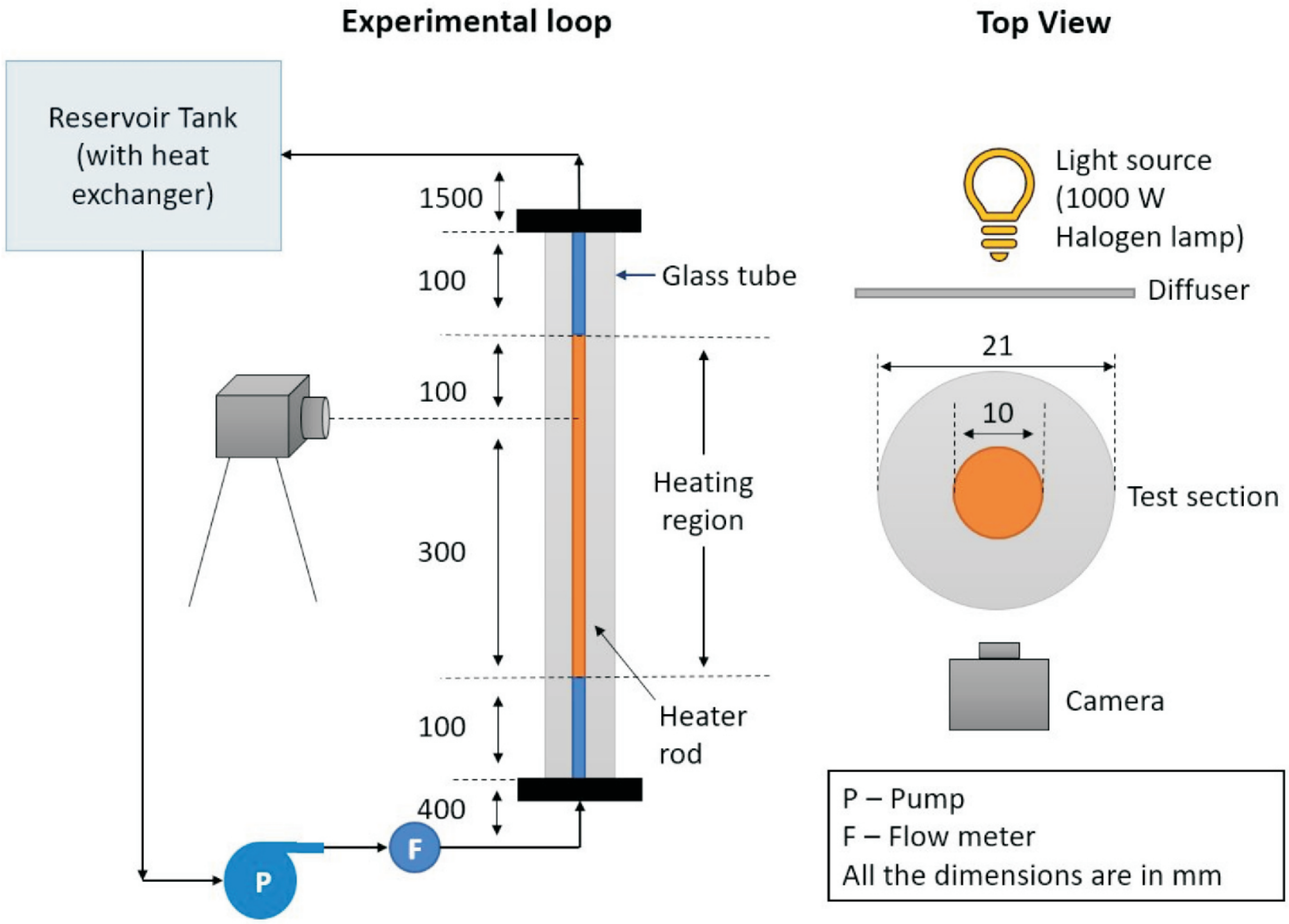

Fig. 1: Experimental Setup (Schematic)

heat transfer and resulting in a sudden increase in the heater surface temperature. The flow physics at CHF has perplexed researchers for many years; it is particularly true, especially at low mass flux conditions, when the operating pressures are low. In literature, many experiments were reported on CHF at low-pressure and low-flow conditions in round tubes[4,5], annular channels with internal heating[6-8], and in rectangular channels with one side and two sides heating[9]. To save the heaters in these experiments, researchers in their experiments mostly kept the heater trip-setpoint at about 50 to 100 K above the water's saturation temperature[6-8]. Hence, the flow physics at CHF, i.e., when the heater temperatures are relatively higher, has been least explored. To understand the flow physics at CHF, especially at low flow and pressure conditions, which are important during accidental conditions of water-cooled reactors and start-up conditions of natural circulation BWRs, we conducted a number of experiments. Details are highlighted below. The results are already reported in the Physics of Fluids journal[10] by the authors; only an abridged version is reported here.

Experimental Setup

Experiments were carried out in an annular test section, a glass tube with an electrically heated rod at the center, with an increased temperature trip-setpoint. The experimental setup consists of a forced convective loop comprising of a centrifugal pump, test section, and a reservoir tank facilitated with cooling coils to act as a heat exchanger (Figure 1). The heater surface, water inlet, and outlet temperatures were measured using 0.5 mm k-type thermocouples using the Yokogawa Data Acquisition system. The flow rate was measured at the inlet using a rotameter. Using Mikrotron Motion BLITZ Cube 4 high-speed camera, the boiling flow patterns were recorded. All the experiments were conducted at atmospheric pressure using demineralized water as a working fluid in the mass flux range of 150 kg/m^2s–200 kg/m^2s with an inlet temperature of 28°C, which are relavant for low pressure and mass flux conditions of LWRs.

Results and Discussions

In the experiments, the heat flux was increased in small steps until an abrupt rise in heater surface temperature was observed, and the corresponding heat flux is defined as CHF. In our experiments, a similar sudden rise in heater surface temperature was observed at CHF; however, surprisingly, the high heater surface temperature was not sustained and got quenched in a short span (Figure 2a and Figure 2b), leading to a sudden decrease of heater surface temperature. This process repeated for a few cycles until the rise in the heater surface temperature reached a very high value (close to 400°C), where the heater power was tripped as a measure of safety to prevent damage to the test section. Several types of flows (flow patterns) occurred in a span of few seconds. Due to rhythmic flow pattern

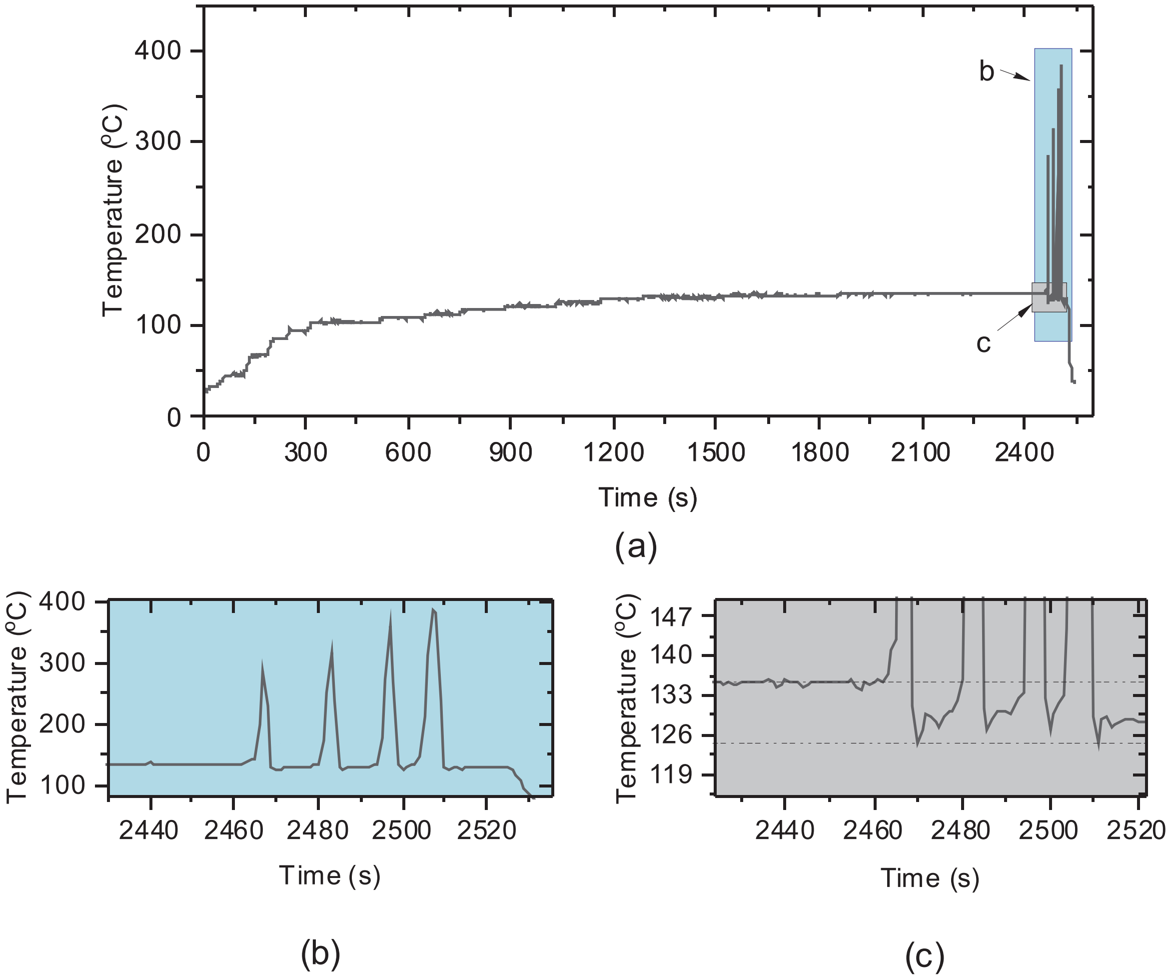

Fig. 2: (a) shows the CHF plot; (b) shows the zoomed-in portion of the same plot in (a) indicating the surface temperature peaks; (c)is a zoomed-in portion of the plot (a) showing the lowest temperature recordings at CHF.

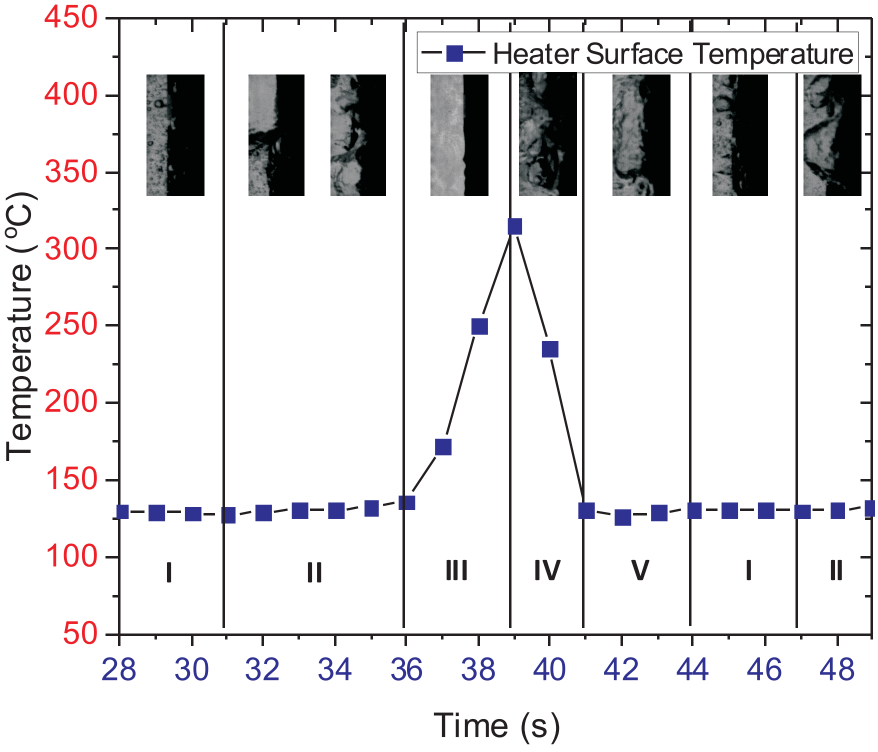

Fig. 3: Variation of heater surface temperature with time in one sonnet cycle

dance at CHF, we named this new CHF mechanism as 'Sonneting Critical Heat Flux'[10].

Sonneting CHF phenomenon is characterized by a unique cyclic flow behavior. Each sonnet cycle can be broadly classified into five zones (Figure 3). In Zone I and Zone II, the heater surface temperature was maintained despite the high heat flux. A sudden heater surface temperature rise was observed in Zone III due to a drastic decrease in heat transfer. An abrupt quenching followed this in Zone IV, with remarkable heat transfer. In Zone V, the heat transfer decreased from the peak value to almost the level of Zone I; nevertheless, in this region, the heater surface temperature was maintained.

Looking at the flow physics at CHF, in each sonnet cycle, initially, we observed bubbles around the heater surface moving upward alongside the liquid, like in classical bubbly flow (Zone I). Within a few seconds, the flow pattern changed to slug/churn flow as the bubbles coalesced to form large-sized bubbles (Zone II). Subsequently, it changed to an unusual reverse annular flow pattern (Zone-III) in which the vapor core moved upward with high velocity while the liquid film moved downward. As the water was not able to wet the heater surface, heater surface temperature increased. However, with time, the liquid film penetration (entrainment) into the vapor core increased due to interfacial shear as both the liquid and vapor are moving in opposite directions.

In addition to this, the coalescence of falling liquid ripples helped in the formation of big disturbance waves. The combined effect resulted in a chaotic flow pattern (Zone-IV). It led to a sudden quenching of the heater surface. The heat transfer was surprisingly very large, which resulted in a reduction in heater surface temperature to a smaller value compared to the value at pre-CHF conditions, e.g., during the fourth sonnet cycle. In fact, the heater surface temperature dropped from 385°C to 125°C, whereas the heater surface temperature at pre-CHF conditions was 135°C. Notably, during the quenching process, the total heat removed was 1.5 times higher than the supplied heat.

This unprecedented quenching process helped in bringing down the heater temperature. After the quenching, the flow pattern changed to slug/churn (Zone-V), following which bubbly flow was restored (Zone-I). This whole process repeated for a few cycles. With each sonnet cycle, the amplitude of heater surface temperature continuously increased and then fell to a lower temperature, which remained almost the same at about 125°C (Figure 2c). The periodicity continuously reduced, as seen in Figure 2. The entire transient of four sonnet cycles occurred in about 70 s. After which the power supply was tripped to save the test section against damage.

Furthermore, it is important to note that for the investigated range of mass flux conditions, the CHF value predicted by the look-up table is about 15% less than the experimental CHF[11].

Conclusion

CHF is generally characterized by an abrupt increase in heater surface temperature. However, the phenomenon is not clearly understood at low pressure and low flow conditions. Considering its importance in accidental conditions of water-cooled reactors and start-up conditions of natural circulation BWRs, we performed a series of experiments to understand the flow physics at CHF.

At CHF, we observed the heater surface temperatures to increase and decrease in a rhythmic fashion. We coined this unique CHF mechanism as 'Sonneting CHF'.

A unique cyclic flow behavior characterizes sonneting CHF phenomenon. In each sonnet cycle, several flow pattern transitions were observed in a span of few seconds. The entire transient at CHF, which involved four sonnet cycles, took place in about 70 s.

Notably, during an unusual reverse annular flow pattern, heater surface temperature was observed to increase. And it was followed by a sudden quenching of the heater surface even when the temperatures were close to 400°C.

During the quenching process, the heat removal rate was about 1.5 times higher than the steady-state heat removal rates, which resulted in a reduction in heater surface temperature to a smaller value compared to the value at pre-CHF conditions.

The CHF look-up table under predicted the experimental CHF value by about 15%.

Sonneting CHF phenomenon has brought new insights to the boiling systems, especially at low flow conditions. It would enable further insights into innovative boiling systems. Moreover, it is important to note that the journey of understanding the limits of boiling is far from over and further efforts are required to unravel its mysteries

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