Heat transfer enhancement in flow boiling using environmentally safe additives

Sameer S. Gajghate, Vaibhav Khandekar and Shrikrushna Chopade

Cogent Engineering (2016), 3: 1210490
Heat transfer enhancement in flow boiling using environmentally safe additives

Sameer S. Gajghate1*, Vaibhav Khandekar1 and Shrikrushna Chopade1

Abstract: This study represents experimental data for flow boiling. Experiments were conducted over the horizontal and angular section with inner heating element with the downward flow. Bubble dynamics & heat transfer enhancement in flow boiling using saturated water and betel nut solution has been studied experimentally. The concentration of surfactant was taken 400–1,200 ppm. Bubble behavior is observed for different angle of water tube as a nucleation site. The bubble dynamics was studied using SONY Cyber-shot camera operating at 30 frames per second at atmospheric pressure. The result obtained by aqueous solution with and without additives shows dissimilarity between temperature difference, heat fluxes & heat transfer coefficient. The upstream interface of the bubble is found to exhibit both forward and reverse movement during bubble growth. The little effect of gravity on the bubble growth rate by the heater glass tube inclination. The enhancement is observed due to surface tension of the environment accepted additive solution.

Subjects: Energy & Fuels; Heat Transfer; Mechanical Engineering

Keywords: heat transfer; additives; bubble; flow boiling

1. Introduction

During the past decades rapid advances in engineering technology related to nuclear energy, ink-jet printers, electric power generation and electronic chips cooling have explore research in a variety of subjects related to heat transfer. Among this research areas, many engineering systems include...
problems related to boiling. In this regard, associated phase change heat transfer has been used substantial to acquire good heat transfer performance. Accordingly, various techniques for enhancement of the boiling heat transfer have been introduced and studied. Typical approaches that have been considered to enhance “Flow” boiling and critical heat flux in particular include (a) oxidation or selective fouling of a heater surface can increase the wettability of the sample liquid used; (b) vibration of heaters to promote the departure of bubbles from a heater surface; (c) extended heater or coating surface to enhance the heat transfer rate; (d) heater or water tube inclination to conducive angle to promote bubble departure from and liquid deposition onto the heater surface. In addition to these methods, recent trends in nano-fluid technology have emerged as a new technique. Flow boiling has an extremely high heat transfer coefficient, and was applied in variety of practices. However, once the heat flux exceeds a critical heat flux point the heated surface can no longer support continuous liquid contact, associated with extensively reduction in the heat transfer efficiency. It may result in a sudden rise of surface temperature of heater surface or a drastic decrease in power transferred in a temperature controlled system. This phenomenon was called the boiling critical point, and the maximum heat flux just before the boiling crisis was usually referred to as critical heat flux (CHF). In this paper we were studying related to saturated flow boiling regimes for water tube with environment friendly additives. The CHF phenomena were studied with emphases on lower pressure with lower flow. The characteristics and parametric trends of the CHF were clarified, and the physical models were derived (see Figure 1).

2. Literature review
Researchers have extensively investigated enhancement by the various enhancement techniques, some of them had carried test on different channel geometry in flow boiling. Result may encourage the heat transfer enhancement in flow boiling was cost effective technique in passive method.

Rojas (2014) gives some lights in the use of capillary pressure structures - porous coatings and micro grooved channels- in enhancing heat transfer in horizontal steam generating channels, like solar parabolic trough receivers for Direct Steam Generation (DSG). Several possible relations between them were shown depending on the porous medium configuration. These relations reduce in playing with parameters for rewetting pipes under DSG conditions, resulting to be critical to determine the configuration of the porous system. Data measurements showed an increase in wetting angle up to 200% against the non-improved pipe. Such improvement was higher at lower temperature range (100–200°C) and lower at higher temperature range (up to 300°C).
Kandlikar (2004) focused on forces due to surface tension and momentum change during evaporation, in conjunction with the forces due to viscous shear and inertia, regulate the two-phase flow patterns and the heat transfer characteristics during flow boiling in microchannels. The usual nucleate boiling heat transfer mechanisms, including evaporation and transient heat conduction in the liquid film adjacent to the contact line region, play an important role. The liquid film under the immense vapor slug evaporates completely at downstream locations thus presenting a dryout condition periodically with the passage of each immense vapor slug. The experimental data and high speed visual observations confirm some of the key features presented in this paper.

Cheol and Soon (2005) presents boiling heat transfer characteristics of nano-fluids with nanoparticles suspended in water were studied using different concentrations of alumina nano-particles. The experimental results found that nano-fluids have lower heat transfer performance compared to pure water in natural convection and nucleate boiling. On the other hand, Critical Heat Flux has been enhanced in not only horizontal but also vertical pool boiling. This was related to a change of surface characteristics by the deposition of nano-particles.

Lei and Tomohiro (2006) conducted experiments on horizontal smooth and micro-fin tubes the flow boiling heat transfer of almost pure CO2 and CO2-oil mixtures. The smooth tube was a stainless steel tube with an inside diameter of 3 mm, and the micro-fin tube was a copper tube with a mean inside diameter of 3.04 mm. The result was considered due to the nucleate boiling being forced by the oil film. The dryout quality decreases much with the increase in mass velocity for the smooth tube, and was almost not influenced by the mass velocity for the micro-fin tube.

Ali (2010) studied Phase change phenomena of a fluid flowing in a microchannel may be exploited to make the heat exchangers closed packed and energy efficient. The experimental flow boiling results for microchannels were reported. Flow boiling visualization results obtained with quartz tube clearly showed the presence of confinement effects and consequently an advanced transition to annular flow for micro channels. Several flow pattern images were captured during flow boiling of refrigerant R134a in quartz tube. Experimental flow boiling heat transfer coefficient results were compared with those obtained using different correlations from the literature.

Singh, Sathyamurthy, Peterson, Arendt, and Banerjee (2010) studied the flow boiling heat flux on a horizontal heater that was heated from below. Experiments were performed for two different flow rates and liquid subcooling. Flow boiling heat flux was enhanced by as much as 180% at boiling developed for silicon substrates coated with carbon nanotubes. MWCNT was less effective enhancement in heat flux as the flow rate and liquid subcooling is increased. This anomalous behavior was explained using flow boiling models reported in the literature.

Magdalena (2012) shows the results of flow boiling heat transfer in a horizontal minichannel, 1 mm deep, 40 mm wide and 360 mm long. The heating element for electronic liquid FC-72 which flows along the minichannel is a thin enhanced alloy. The experiments engage the enhanced heating foil with various depressions, distributed diversely on the surface. The main objective of the paper was to determine the void fraction for cross-sections of selected images for increasing heat fluxes supplied to the heating surface. The results were presented as the void fraction dependence along the minichannel length for the selected cross-sections. The investigation has been intended to determine the correlation for the calculations of the Nusselt number as a function of variable parameters.

Chen (2012) work on flow boiling has an extremely high heat transfer coefficient, and was applied in variety of practices. Result show sudden rise of surface temperature in a heat flux controlled system, or a desperate decrease in power carried in a temperature controlled system. A great number of empirical
correlations and physical models had proposed. Unfortunately, there exists a shortage of CHF data in low pressure/low flow/subcooled region. CHF were clarified, and the physical models were derived.

Gajghate, Acharya, and Pise (2013) concludes in their experimental study as the maximum level of enhancement was observed up to 2,600 ppm concentration of aqueous ammonium chloride as additive in nucleate pool boiling heat transfer. For Concentrations more than 2,600 ppm, outstanding enhancement was not recorded. Enhancement observed was due to the change in the thermo physical properties of the aqueous solution. It was observed that as ammonium chloride was pure water, the surface tension of the mixture considerably reduces.

Fanghao et al. (2014) worked on flow boiling with deionized water in silicon (Si) micro channels was extremely enhanced in a single annular flow boiling regime allow by super hydrophilic Si nanowire inner walls. The significantly Promoted nucleate boiling, persuade liquid film renewal, and enhanced thin-film evaporation in the self-stabilized and single flow boiling regime were the primary reasons behind the significant heat transfer enhancements during flow boiling.

Gajghate, Acharya, Pise, and Jadhav (2014) work encouraged and show that a small amount of surface active additive makes the nucleate boiling heat transfer coefficient considerably much higher, and that there was an optimum additive (500–1,000 ppm) concentration for higher heat fluxes. A most appropriate level of enhancement was observed up to a certain amount of additive 500–1,000 ppm in the tested range.

Seung et al. (2015) founded a very interesting characteristic of nanofluids was their ability to significantly enhance the CHF. Nanofluids were nanotechnology-based colloidal dispersions engineered through the stable suspension of nanoparticles. Experiments were performed in round tubes with an inner diameter of 0.01041 m and a length of 0.5 m under low pressure and low flow conditions at a fixed inlet temperature using water, 0.01 vol % Al₂O₃/water nanofluid, and SiC/water nanofluid. It was discovered that the CHF of the nanofluids was enhanced and the CHF of the SiC/water nanofluid was more enhancement observed than the Al₂O₃/water nanofluid.

3. Experimental set-up
The Figure 2a, show the block diagram of experimental set prepared by us for experimental to study the flow pattern with different tube angle with the additives for heat transfer enhancement in flow boiling also Table 1 show the specification of instruments used.
4. Experimental procedure
Preparation for the experiments included bringing the pressurized tank up to the desired water inlet temperature and pre-heating the tube to 10°C above the intended inlet temperature as shown in Figure 2b. The tube was set to the desired angle and once the operating conditions were reached, the valve was opened to direct the flow into the tube. Flow rates were set using the flow control valve, and the power to the pre heaters was controlled to give at least 60°C temperature rise above the inlet temperature. Each experimental condition was held until the tube reached thermal steady-state, which was determined by monitoring the change in the determined heatflux from the measured temperatures.

If the temperatures and the heat flux held steady for 3 min, it was seemed that the system had reached steady-state and that instant data were recorded. Temperature data from the embedded thermocouples were used to calculate the local heat flux from the heaters to the tube surface and to extrapolate the actual tube surface temperature from the top row of thermocouples embedded just beneath the surface based on unidirectional heat conduction in the plate. The inlet temperature was calculated by using thermocouple which is inserted at the inlet port same as that the outlet temperature has been measured.

5. Results and discussion
As the work is in flow boiling it should be a comparative study, because it gives the extensive knowledge regarding the bubble regimes with varying heat flux & excess temperature. The extensive experimentation of flow boiling was carried for normal water, pure water with & without surfactant of varying concentrations (i.e. 400, 800 and 1,200 ppm) of betel nut which is eco-friendly. Comparative

---

Table 1. Instruments specification

| Sr. no. | Part name   | Capacity and accuracy | Made/type |
|---------|-------------|-----------------------|-----------|
| 1       | Water tank  | 35 l                 | PVC       |
| 2       | Flow meter  | –                     | Acrylic   |
| 3       | Ammeter     | 0.2 A                 | Analog    |
| 4       | Dimmerstat  | 2 kVA                 | Analog    |
| 5       | Temp. indicator | 1.0°C              | Digital   |
| 6       | Voltmeter   | 20 V                  | Analog    |
| 7       | Heater      | 1500 W                | Nichrome  |
| 8       | Glass tube  | $1.22 \times 10^{-3}$ m$^3$ | Barosilicate |
| 9       | Thermocouple | 0.1°C                | K-type    |

---

Figure 2b. Actual working setup for experimental study.
studies of results of surfactant were broadly discussed into two categories as boiling behavior and boiling curves. The boiling phenomenon mainly depends on physical properties of fluid that are density, surface tension and kinematic viscosity. The addition of a small amount of surfactant does not affect the density of the solution but it slightly increases the viscosity if surfactant is polymeric. The enhancement of heat transfer is might be due to the depression of surface tension. The data collected during experimentation are tabulated in the form of graphs. The results are described as follows.

5.1. Bubble behavior
Bubbles form a blanket over the surface of heater, which observed in water. The reason is due to effect of addition of varying concentration of betel in water, decreases the surface tension of solution and hence the forces acting on bubbles are smaller and detach it rapidly from the heater surface in addition of betel nut in water. Also surfactant activates the number of nucleation sites on the same heater surface. The results show that the velocity slightly increases with varying concentrations from 400 to 12,000 ppm. It might be due to addition of surfactant, surface tension force decreases and hence resistance to bubble motion is also decreases. Due to this reason velocity of bubble slightly increases at CHF and for further heating velocity decreases. The comparison of normal water, distilled

![Figure 3. Photo images of bubble for normal water at different tube angles with varying heat flux.](image)

(a) $0^\circ$, $q=637.25\text{W/m}^2$ (b) $15^\circ$, $q=669.6\text{W/m}^2$

(c) $17^\circ$, $q=787.25\text{W/m}^2$ (d) $19^\circ$, $q=797.23.67\text{W/m}^2$

![Figure 4. Photo images of bubble for distilled water at different tube angles with varying heat flux.](image)

(a) $0^\circ$, $q=636.65\text{W/m}^2$ (b) $15^\circ$, $q=687.25\text{W/m}^2$

(c) $17^\circ$, $q=806.77\text{W/m}^2$ (d) $19^\circ$, $q=816.77\text{W/m}^2$
Water, betel nut in water on the basis of bubble behavior had shown in Figures 3–7, with varying angle (0°, 15°, 17° and 19°) of glass tube containing heater. Also Figures 3–7 is Photo images of bubble of betel nut concentration in pure water, distilled & normal water for different heat fluxes (W/m²).
5.2. Boiling curve

From Figure 8, found that as the temperature difference increases with change in heat flux. The graph will increase to a CHF point and then it will falls down. Best possible result can be obtained at an angle of 15° and 19°. At this angle at minimum temperature difference we can get the maximum heat flux. As angle increases gravity level of water changes. In Figure 9 Improvement observed with distilled water compare to normal water for same angle. Here observed that compared to normal water temperature difference is minimum increase in heat flux; it means heat transfer improvement where found in distilled water for varying tube angle 17° and 19°.

In Figure 10 distilled water result shows that as angle goes on increasing heat flux as well as heat transfer coefficient increases. To the certain angle it goes on increasing after that it will decrease and for tube angle 17° it will give maximum heat transfer coefficient at low heat flux. As well as at 15° it will give the better result as compared to the next angle this is due to the effect of gravity on flow boiling.
A result for Betel nut with varying concentration was observed in Figures 12–14. As heat flux goes on increasing heat transfer coefficient also increases to an extent it give the maximum heat transfer coefficient at minimum temperature at an angle of 0º and 17º found in Figure 11. So, much improvement was observed in distilled water compared to normal water on 17º angle of tube. The effect of additives on flow boiling and change in tube angle result is fabricated in Figures 12–14.

From Figure 12, shows that effect of addition of Betel nut powder on boiling, increased in heat transfer rate at minimum temperature were observed. At varying tube angle from 0–17º graph goes on increasing after further inclination of tube angle above 17º graph nature goes on decreasing it is due to effect of surface tension on the boiling by using surfactant with different concentrations of 400 and 800 ppm; but for the 1,200 ppm concentration the high heat transfer coefficient was observed.
In experiment we conceive that at constant mass flow rate betel nut as additive can enhance the heat transfer coefficient, which is believed to be a significant benefit for flow boiling. As noted, the effect of adding additives heat transfer rate is progressively larger for increasing T. It is obvious, from Figures 12–14, that heat transfer additive betel nut gives much higher average heat transfer coefficients than heat transfer rate compared to other additives.

It can be clearly seen that heat transfer additive betel nut is more useful for the purpose of this study. The effects of varying concentration (400–1,200 ppm) on heat transfer co-efficient and heat flux. A 30% increase in the average heat transfer coefficient was obtained at 800 ppm on 17° of tube angle. The figure shown optimum quantity of betel nut can be select for the boiling process in base fluid. At 1200 ppm the result was better for boiling process at low excess temperature with comparing water at 19°; as the concentration increases; decreases the ΔTexcess which is better result for water with betel nut which is the aim of experimentation work.

5.3. Uncertainty analysis
The uncertainty analysis in experimental measurements is very useful in assessing the deviation in data, and identifying the source of any abnormal error. The voltmeter and ammeter used for the experimentation were within ±1 V and ±0.001 A accuracy level respectively. The uncertainty in the measurement of heat flux was ±7.5%. The bubble diameter in both water and aq. surfactant solution was measured with accuracy level of ±0.25 mm (±5%).

6. Conclusion
Heat transfer rate in increases in distilled water as per results than the normal hard water. As in case of distilled water it is a pure water having boiling point exact 100°. This gives the better results than normal water. Again for the further enhancement we are using the surfacing agent to the water for identifying the results by using eco-friendly accepted additive named as betel nut. When we are adding the surfacing agent such as betel nut powder then it reduces the boiling point of water which results in heat transfer enhancement. At minimum temperature, from the graph at different parts per million (ppm) we get the results that are enhancement in heat transfer at less degree than the distilled water.

As the inclination goes on increasing the heat flux and heat transfer coefficient varies but at the inclination of 17° degree the best possible result were drawn for the normal hard water. And as per above conclusion best possible results in distilled water after addition of surfactant betel nut powder it can be drawn at 15° and 17° That conclude heat transfer enhancement is done after addition of betel nut. The flow boiling experiments gave similar heat transfer results; they exhibited that the smaller diameter channels resulted in higher heat transfer coefficients.
Nomenclature

- \( h \): heat transfer coefficient, \( \text{W/m}^2 \text{K} \)
- \( K_I \): current, Amp
- \( I \): length of glass tube, mm
- \( \text{ppm} \): concentration, parts per million
- \( q \): heat flux, \( \text{W/m}^2 \)
- \( Q \): power capacity, W
- \( t \): thickness of glass tube, mm
- \( \Delta T \): temperature difference, K
- \( V \): volt, V

Acknowledgments

Project is carried out in Applied thermodynamics laboratory-I, Dr. Ashok Gujar Technical Institutes’, Dr. Daulatrao Aher College of Engineering, Karad, Maharashtra under the guidance of Professor Sameer S. Gajghate.

Funding

This work was financially supported by the Dr. Ashok Gujar Technical Institutes’, Dr. Daulatrao Aher College of Engineering, Karad 415124, Maharashtra, India [grant number 02082014/2015].

Author details

Sameer S. Gajghate1
E-mail: mtech_sameer@yahoo.in
ORCID ID: http://orcid.org/0000-0002-8781-7122
Vaibhav Khandekar1
E-mail: khandekar.vaibhav@yahoo.com
Shrikrushna Chopade1
E-mail: shrikrushnachopade101@gmail.com

1 Department of Mechanical Engineering, AGTIS’ Dr. Daulatrao Aher COE, Karad 415124, Maharashtra, India.

Citation information

Cite this article as: Heat transfer enhancement in flow boiling using environmentally safe additives, Sameer S. Gajghate, Vaibhav Khandekar & Shrikrushna Chopade, Cogent Engineering (2016), 3: 1210490.

Cover image

Source: Authors.

References

Ali, R. (2010). Phase change phenomena during fluid flow in micro channels (Doctoral thesis). Division of Applied Thermodynamics and Refrigeration, Department of Energy Technology Royal Institute of Technology, Stockholm. Retrieved from http://www.diva-portal.org/smash/get/diva2:372785/FULLTEXT01.pdfErik
Chen, Y. (2012). Critical heat flux in subcooled flow boiling of water. In M. Salim Newaz Kazi (Ed.), An Overview of Heat Transfer Phenomena. In Tech. doi:10.5772/52307
Cheol, B., & Soon, H. C. (2005, June). Boiling heat transfer performance and phenomena of \( \text{Al}_2 \text{O}_3 \)-water nano-fluids from a plain surface in a pool boiling. International Journal of Heat and Mass Transfer, 48, 2407–2419. doi:10.1016/j.ijheatmasstransfer.2004.12.047
Fanghao, Y., Xianming, D., Yaov, P., Ping, C., Jamil, K., & Chen, L. (2014, January). Flow boiling phenomena in a single annular flow regime in micro channels (I): Characterization of flow boiling heat transfer. International Journal of Heat and Mass Transfer, 70–715. doi:10.1016/j.ijheatmasstransfer.2013.09.058
Gajghate, S., Acharya, A. R., & Pise, A. T. (2013, November). Experimental study of aqueous ammonium chloride in pool boiling heat transfer. Journal of Thermal Energy Generation, Transport, Storage, and Conversion, 27, 113–123. doi:10.1080/08916152.2012.757673
Gajghate, S. S., Acharya, A. R., Pise, A. T., & Jadhav, G. S. (2014). Experimental study of heat transfer enhancement in pool boiling by using 2-Ethyl 1-Hexanol an additive. Applied Mechanics and Materials, 592–594, 1601–1606. doi:10.4028/www.scientific.net/AMM.592-594.1601
Kandlikar, S. G. (2004, Feb). Heat transfer mechanisms during flow boiling in microchannels. Journal of heat transfer, 126, 8–16. doi:10.1115/1.1643090
Lei, G., & Tomohiro H. (2006). Experiments on flow boiling heat transfer of pure \( \text{CO}_2 \) and \( \text{CO}_2 \)-oil mixtures in horizontal smooth and micro-fin tubes. International Refrigeration and Air Conditioning Conference, July 17–20, 2006 (Paper 770, pp. 5–8). Retrieved from http://docs.lib.purdue.edu/iracc/770
Magdalena, P. (2012, November). Experimental study of flow boiling heat transfer in a rectangular minichannel by using various enhanced heating surface. Journal of Physics Conference Series, 395, 012136. doi:10.1088/1742-6596/395/1/012136
Rojas, M. E. (2014). Heat transfer enhanced parabolic trough receiver for DSG with capillary systems. Retrieved from http://ptp.irb.hr/upload/maple/kuca/19_19.m_e_rojas_heat_transfer_enhanced_parabolic_trough_receiver.pdf
Seung, W. L., Seong, D. P., Seong, K., Seong, M. K., & Han, S., Dong, W. L., & Cheol, B. (2015, June). Critical heat flux enhancement in flow boiling of \( \text{Al}_2 \text{O}_3 \) and \( \text{SiC} \) nanofluids under low pressure and low flow conditions. Nuclear Engineering and Technology, 47, 398–406. doi:10.5516/NET.04.2012.516
Singh, N., Sathyamurthy, V., Peterson, W., Arndt, J., & Banerjee, D. (2010, April). Flow boiling enhancement on a horizontal heater using carbon nanotube coatings. International Journal of Heat and Fluid Flow, 31, 201–207. doi:10.1016/j.ijheatfluidflow.2009.11.002
