

# Surface Energy Effect on the Phase-Change Heat Transfer and the Fluidics

**ATUL A-P. PATIL.**

Mechanical Engineering Department, North-Eastern Regional Institute of Science and Technology [NERIST], Nirjuli-791109, Arunachal Pradesh

E-mail: patilap00@yahoo.co.in, pastcommu@gmail.com,  
patilap00@rediffmail.com.

Now at **Reverend Universalis**, [Organisation for Science, Technology, Arts and Medicine], Vinayak Complex, Nandura Road, Khamgaon-444303, Dist.: Buldhana, Maharashtra of India

\*Corresponding author's E-mail: patilap00@yahoo.co.in,  
pastcommu@gmail.com

**Abstract:** Boiling-heat-transfer and condensation-heat-transfer both are complex phenomena and are not yet completely understood from energy efficiency point of view as well as from their own behavioural understanding point of view. A theory of interphasial surface energy and intraphasial surface energy has been proposed here in this research paper. This theory has been developed further successfully to yield a non-dimensional number etc. to explain boiling-heat-transfer and condensation-heat-transfer. This theory can be thus successfully utilised to gain more insights into the basics of boiling-heat-transfer and condensation-heat-transfer from behavioural point of view as well as from energy efficiency point of view. Better heat transfer systems pertaining to liquid-gas

phase-change and gas-liquid phase change phenomena could be brought into reality by incorporating this new theory. This theory has been put forth to serve as a tool as well as platform for the study of various aspects of boiling-heat-transfer and condensation-heat-transfer.

The same theory is extended further for the fluid flow phenomenon and is discussed here in brief. Need of further research validating this theory has been raised for gaining deeper know-how of the said phenomena.

# 1. INTRODUCTION

Boiling (Liquid-Gas-Phase-change) heat transfer and condensation (Gas-Liquid-Phase-Change) heat transfer have applications in various fields e.g. chemical engineering, mechanical engineering, nuclear engineering etc. The objective of the design engineer in all the above mentioned fields is to select and design a material system that will transfer the phase-change heat *i.e.* boiling-heat in the case of the boiling process and condensation-heat in the case of the condensation process, with minimum possible temperature difference between the respective phase and the solid wall. But, because of the complexity of these two phenomena and their underdeveloped understanding, much of the contemporary research is driven towards studying the basic phase-change mechanisms *i.e.* boiling-heat-transfer mechanism and condensation-heat-transfer mechanism, so that it would be possible to predict the boiling-heat-transfer behaviour and condensation-heat-transfer behaviour a priori. Also, the capability to predict boiling-heat-transfer conditions and condensation-heat-transfer conditions from different factors viz. boiling material surface characterisation and condensation material surface characterisation, thermofluid properties would

enable the performance of the boiling-heat-transfer and condensation-heat-transfer material systems to optimise. The material system required for this optimised heat transfer should possess the peculiarities like durability, longevity, ability to work at different pressures, temperatures and heat flux levels, ability to adopt the variations in pressure, temperature and heat flux, workability with different forms of fluids at various operating conditions and under the influence of different surrounding fields, ecofriendliness, manufacturability, economy etc. But, because of the complexity of the boiling-heat-transfer and condensation-heat-transfer phenomena, which remain unaffected inspite of various attempts to unfold it, the design engineer faces problems in designing energy efficient boiling-heat-transfer and condensation-heat-transfer systems and in optimising the energy systems' behaviour along with their control.

Many scientists extended their whole life to reveal these phenomena of boiling and condensation, individually or jointly. It is to be noted here that all these people not only contributed their material belongings but their emotional life as well. And, with their contributions, different techniques for catering the boiling-heat-transfer and condensation-heat-transfer have been developed and those can be grouped into active & passive ones [1]-[5].

A yard stick is required to quantify and qualify the boiling-heat-transfer and condensation-heat-transfer, which would also be helpful in predicting the boiling and condensation behaviours. Moreover, there is a need of a suitable platform over which the boiling and condensation performances could be studied, and the safe, energy efficient and cost effective heat transfer material systems could be designed and operated successfully for the desired period. [6]-[8] successfully putforth the solid-liquid surface energy as a tool towards this direction for the boiling-heat-transfer and condensation-heat-transfer. Collective lists of typical preceding research in the boiling-heat-transfer and condensation-heat-transfer are given in [6]-[8].

In this research paper, a theory of cohesive and adhesive surface energies, which is an extension of the solid-liquid surface energy approach used in [6]-[8], is proposed along the Newtonian theory of particles [9] to explain both the boiling-heat-transfer and condensation-heat-transfer.

Lavoisier [10] developed forward the Newtonian idea (perhaps the model of relating the separation of the liquid particles and the application of heat, has initially been due to Halley [11]) that all bodies are made up of particles and these particles experience both the attractive as well as the repulsive forces among themselves. And, when the attractive force is overcome, phase change will proceed. The theory of cohesive and adhesive energies is a consequence of applying the Newtonian theory of the particles with the surface energy postulates, to develop the logical understanding of boiling-heat-transfer and condensation-heat-transfer.

## 2. SURFACE ENERGY THEORY

A fluid molecule, which is in contact with a solid heat transfer surface, is under the action of the tensile forces from the solid heat transfer surface side and from other fluid molecules from the inner layers of it. The solid-fluid force yields surface energy (cohesion) of solid-fluid and the fluid-fluid force yields adhesion energy of fluid-fluid *such as* liquid-liquid adhesion energy, gas-gas adhesion energy depending upon the phase under consideration. The fluid-fluid adhesion force *i.e.* liquid-liquid/gas-gas adhesion force is nothing but the intermolecular forces of attraction among the molecules of the phase under consideration.

A) Boiling: The phenomenological definition of boiling is the

existence of sustained bubbles that break free of the surface. For boiling, the interfacial surface energy (cohesion) is nothing but the interfacial solid-liquid surface energy and the adhesion energy is nothing but the liquid-liquid intermolecular forces of attraction.

A bubble is a vapour phase substance. During the boiling, this bubble *i.e.* vapour phase substance, forms from a certain molecule of liquid by breaking that liquid molecule's bondages with other surrounding liquid molecules *i.e.* by overcoming the liquid-liquid intermolecular forces of attraction; in other words the adhesion energy.

By making the interfacial solid-liquid surface energy (cohesion energy) larger than the adhesion energy, the bubble formation will be characterised by larger heat removal. Increasing the interfacial solid-liquid surface energy *i.e.* cohesion energy, means increasing the affinity of the liquid substance with the solid boiling heat transfer surface. This means more heat energy is required to break the solid-liquid bond and form vapour (*i.e.* to form solid-vapour bond, the vapour being in contact with the solid heat transfer surface). More the affinity *i.e.* cohesion energy of the liquid substance with the solid boiling heat transfer surface, more will be the boiling heat absorbed from the solid boiling heat transfer surface. Thus, the bubble formation will be characterised by more heat removal from the solid boiling heat transfer surface.

Now, a Non-dimensional number is defined as below:

$$\text{Ratio; } R = \frac{\text{solid-fluid surface energy}}{\text{fluid-fluid adhesion energy}} \quad (1)$$

which for boiling becomes as:

$$\text{Ratio; } R = \frac{\text{solid-liquid surface energy}}{\text{liquid-liquid adhesion energy}} \quad (2)$$

where liquid-liquid adhesion energy: intermolecular force of attraction among the liquid molecules themselves.

Considering the case of boiling-heat-transfer, following cases can be envisaged as discussed above:

- i. When  $R \geq 1$  small scale heat transfer will take place
- ii. When  $R \gg 1$  vigorous heat transfer will take place
- iii. When  $R < 1$  heat transfer in small extent will take place
- iv. When  $R \ll 1$  extremely poor heat transfer will take place

{provided the following condition for the heat transfer enhancement owing to bubble departure from the heater surface is met:

$$\text{Attraction Energy}_{gg} \geq \sigma_{sl} + \frac{\text{Bubble Weight}}{r} \quad (3)$$

where

$r$ : the characteristic length which can be either the bubble radius  
 or  $\left( \frac{\text{Bubble Volume}}{\text{Bubble Surface Area}} \right)$ .

Attraction Energy<sub>gg</sub> = Stabilised form of Energy (*i.e.* energy of attraction) among the molecules of the fully transformed gaseous-phase keeping them in union amongst each others (*i.e.* without breakage), and thus making them to leave the heat transfer seat. And, as “ $r$ ” becomes larger for a given set of conditions, the bubble departure frequency increases thus enhancing the heat transfer from the heat transfer surface vide (3).

$\sigma_{sl}$  = solid-liquid surface energy}

B) Condensation: For condensation, the interfacial surface energy (cohesion) is nothing but the interfacial solid-vapour (or solid-gas) surface energy and the adhesion energy is nothing but the vapour-vapour (or gas-gas) intermolecular forces of attraction.

Condensation is characterised by droplets. A droplet is a liquid phase substance. During the condensation, this droplet *i.e.* liquid phase substance, forms from a certain molecule of vapour by breaking that vapour molecule's bondages with other surrounding vapour molecules *i.e.* by overcoming the vapour-vapour intermolecular forces of attraction; in other words the adhesion energy.

Increasing the interfacial solid-vapour surface energy *i.e.* cohesion energy, means increasing the affinity of the vapour substance with the solid condensing heat transfer surface. This means more heat energy is released after breaking the solid-vapour bond and forming the droplet (*i.e.* forming solid-liquid bond, the droplet being in contact with the solid heat transfer surface). More the affinity *i.e.* cohesion energy of the vapour substance with the solid condensing heat transfer surface, more will be the condensation heat released to the solid condensing heat transfer surface. Thus, the droplet formation will be characterised by more heat release to the solid condensing heat transfer surface.

In the similar fashion as done for boiling, condensation could be explained with the help of

$$\text{Ratio; } R = \frac{\text{solid-gas surface energy}}{\text{gas-gas adhesion energy}} \quad (4)$$

When

- i.  $R \geq 1$ , small scale heat transfer will take place
- ii.  $R \gg 1$ , vigorous heat transfer will take place

iii.  $R < 1$ , heat transfer in small extent will take place

iv.  $R \ll 1$ , extremely poor heat transfer will take place

{provided the following condition for the heat transfer enhancement owing to droplet removal from the condenser surface is met:

$$\sigma_{sl} \leq \text{Repulsion Energy}_{ll} + \frac{\text{Droplet Weight}}{r} \quad (5)$$

where

$r$ : the characteristic length; sufficient for that droplet, to have the momentum to slide or vacate its seat, over the condenser surface, and which could be

$$\left( \frac{\text{Droplet Surface Area}}{\text{Droplet Perimeter subtended at the solid-heat transfer surface}} \right)$$

or droplet radius

Repulsion Energy<sub>ll</sub> = Stabilised form of Energy (*i.e.* energy of repulsion) among the molecules of the fully transformed liquid-phase making them separate from each others (*i.e.* without uniting) and thus thereafter making them to leave the heat transfer seat. And, as “ $r$ ” becomes smaller for a given set of conditions, the droplet departure frequency increases thus enhancing the heat transfer from the heat transfer surface vide (5).

$$\sigma_{sl} = \text{solid-liquid surface energy} \}$$

Various applications and the procedures which involve the liquid-gas phase-change heat transfer and the gas-liquid phase-change heat transfer; are also explainable with the help this non-dimensional number, which can also be expressed as

$$\text{Ratio; } R = \frac{\text{Surface Energy}_{\text{interphase}}}{\text{Surface Energy}_{\text{intrapase}}} \quad (6)$$

The boiling-heat-transfer and the condensation-heat-transfer cases described above have been dealt by considering the heat transfer surface made up of the solid phase. For the other cases also, where the heat transfer surface is other than the solid phase *i.e.* heat transfer surface being of the liquid or the gaseous phase, the theory gives a logical platform. In other words, when the fluid is to be heated or cooled, it could be brought in contact with any other liquid or gas at appropriately higher or lower temperature. For example, consider a situation where a liquid is in contact with high temperature gaseous phase; *say* air, the liquid can experience the transition to gaseous phase. Hence, in this cases; the non-dimensional number;  $R$  can be elaborated as

$$\text{Ratio; } R = \frac{\text{surface energy owing to cohesion}}{\text{fluid-fluid adhesion energy}} \quad (7)$$

and subsequently  $R$ , becomes the ratio between the cohesive and adhesive surface energies.

The ratio  $R$  conceptualised here is in agreement with the concept of Boskovic [12] meant for the evaporation and ebullition, and can be said to be a proceeding of the Newtonian School of thoughts. Boiling-heat-transfer and condensation-heat-transfer; in specific, and the liquid-gas phase-change heat transfer and the gas-liquid phase-change heat transfer; in general, thus can be explained, operated upon and optimized in the equipments on the basis of this non-dimensional number, and thus on the basis of this theory.

This theory not only acts as a tool but also serves as a platform for gaining deeper know-how of the said phenomena and the system performance etc.

Further extension of this theory is required for more insights into

several enumeral aspects of the study of the said liquid-gas and gas-liquid phase-change heat transfer phenomena, and for the designing and operation of efficient, effective, safe and economical heat transfer systems working on these phenomena.

C) Fluidics: There are several situations where the fluid is required to remain adhered to the solid-body viz. situations of the flow past a body. It is required that flow doesn't separate *i.e.* boundary layer separation doesn't occur and fluid remains adhered to the skin of the body while flowing. Thus, in the case of the boundary layer problems, it is required that the fluid remains adhered to the skin of the solid body. There are also situations where the fluid is required to accelerate or decelerate viz. flowing/moving bodies etc. In case of fouling, it is required to avoid the particle deposition which could be achieved if the particle faces opposing-forces from the solid-wall. Fouling could also be avoided if the fluid near the solid-wall accelerates so that the particle doesn't settle at the solid-wall. In micro-fluidics, it is essential for the fluid to flow/move in a particular direction. In order to avoid the corrosion, it is essential that the flow containing the moisture; only and not the whole flow, is directed away from the surface to be protected.

The Surface Energy theory here is extended with reference to the above for the fluidics. The standard equations of Euler and Bernoulli; when amalgamated with the surface energy gradient, could help dealing with the above mentioned problems, amongst the others. The Patent in this regard for various applications is in the Patent Office and is described in the subsequent Part.

### 3. CONCLUSION

A theory has been putforth to explain the boiling-heat-transfer and condensation-heat-transfer, in terms of cohesive and adhesive surface energies. A non-dimensional number has been defined as the

ratio of the solid-fluid surface energy and the fluid-fluid adhesive energy, and also in terms of the ratio of the interphase and the intraphase energies. This theory can be utilized for better and concrete explanation of the boiling-heat-transfer and condensation-heat-transfer. Also, with the help of this theory, novel applications of heating and cooling could be designed and operated successfully.

The theory has been proposed for further advancement; including for the fluidics, towards more understanding of various deeper aspects of the said processes, and for the successful designing and operation of the heat transfer and fluid flow equipments and utilities respectively.

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