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# EFFECT OF WALL SURFACE ROUGHNESS ON DROPLET COOLING OVER A RECTANGULAR HEATED PLATE IN AN ENCLOSURE

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## ABSTRACT

Study of evaporation of single droplet plays a very important role in analyzing the process operations of fuel cooling and spraying systems. This has been a pioneering area of research among chemical and heat transfer engineers. In the present work, an experimental and numerical study of the dynamics of droplet evaporation inside a rectangular enclosure is carried out. The width of the enclosure is less than the spreading radius of the droplet which generates two contact angles, one with the heated surface and the other with the enclosure and this makes the study important. The droplet absorbs a considerable amount of heat as it evaporates on the plate thereby reducing its temperature. The introduction of enclosure enhances the cooling effect when compared to droplet cooling in the plate without enclosure. The effect of heat transfer with the introduction of rectangular enclosure is studied based on the numerical analysis. Turbulence modelling is used with standard wall treatment to study the effect of surface roughness on droplet evaporation in the presence of a rectangular enclosure. A change in the dynamics of the droplet with change in surface roughness of the heated plate and wall enclosure is reported in terms of variation in contact angle and heat transfer characteristics.

## INTRODUCTION

Analysis of evaporation of water droplets over heated surfaces is of great interest to engineers because of its diverse applications in the field of heat transfer. The characterization of the dynamics of water droplets is pivotal in studying the cooling effect produced on the heated plate. The cooling of a hot surface with water droplets is one of the effective ways used in various cooling systems. It has wide applications in nuclear reactors, turbines etc. In droplet cooling technique, the major factors that affect the cooling process are droplet size, nature of the heated plate and wall surface roughness.

Initial studies on water droplets levitating on a hot surface were carried out by Tamura and Tanaswa [1]. They classified four regimes during droplet evaporation as: film evaporation, nucleate boiling, transition and spheroidal vaporization. Analysis of droplet mechanics at various initial stages of droplet evaporation was presented by Hubbard et al [2]. Droplet evaporation at initial stages requires detailed analysis as it differs considerably from quasi steady state. An important parameter to characterize the droplet dynamic characteristics is the contact angle. Bernardin et al. [3] analysed the contact angle dependence for water droplets on Aluminium surfaces. It was seen from the analysis that the contact angle is an important parameter to be studied to understand the dynamics of water droplets. They also developed an empirical relation between the contact angle and the temperature of the heated surface. Surface characteristics play an important role in changing the dynamics of water droplet during evaporation. Surface roughness and its effects on droplet evaporation was systematically analysed by Kamnis and Gu [4]. Wachters and Westerling [5] described experimental observations involving the dynamics of droplet of size 2mm in a gold surface. Yet another interesting study of single droplet on a glass surface was reported by Kurokawa and Tada [6]. Xiong and Yuen [7] studied the impact of single droplet of water and hydrocarbon fuels. Di Marzo and Evans [8] performed experiments to analyze variation in temperature with droplet impingement on an aluminium surface.

Though considerable attention has been paid to experimental analysis, numerical studies on droplet dynamics have gained acceptance widely. This is because, numerical analysis provides an easier means to analyse transient characteristics such as velocity and temperature distribution. Out of several numerical approaches available for multiphase flows, Volume Of Fluids is a robust modelling tool used to study the phase fraction distributions during droplet evaporation as presented by Harshavardhan et al [9]. In the present work, this tool has been effectively used along with experimental support to understand the droplet dynamics and heat transfer characteristics on the evaporation of droplet on heated plate surrounded by an enclosure. The presence of enclosure is found to play a major role on the cooling of the heated plate. The effect of wall surface roughness on the droplet dynamics is also studied

## NOMENCLATURE

| | |
|---|---|
| **t** | **Time (s)** |
| **v** | **Velocity (m/s)** |
| **F** | **Body force (N)** |
| **T** | **Temperature (K)** |
| **$\alpha$** | **Volume fraction** |
| **$\rho$** | **Density (kg/ m$^3$)** |
| **$\mu$** | **Dynamic Viscosity(Pa s)** |
| **$\sigma$** | **Surface tension (N/m)** |
| **$\tau_w$** | **Wall shear stress (N/m$^2$)** |

## EXPERIMENTAL SETUP

The experimental setup used in the present work is the same as that presented by Harshavardhan et al [9]. It consists of a stainless steel plate kept over a heater setup with an aluminium rectangular enclosure. AC voltage is supplied to the heater setup and is controlled using a single phase 0-250 V Variac. A cartridge type heater is kept inside a wooden box filled with MgO powder which ensures uniform distribution of heat to the stainless steel plate. The dimensions of the stainless steel plate are 6.5 cm X 6.5 cm X 0.3cm and that of the aluminium enclosure are 10cm X 10cm X 3.3cm. Ultraviolet Conditioned water was used to prevent deposition. A high speed camera (Basler CMOS Model No: acA2000 monochrome, with a Zooming Lens Navitar Zoom (7000, 18-108 mm)) is used to capture the droplet dynamics and behaviour of droplets and record the evaporation lifetime continuously. The camera is capable of recording real time images at the rate of 1500 fps for a 32 x 32 size resolution. The temperature is measured simultaneously using a K-type thermocouple connected to a National Instruments 9211 Data acquisition system. The experiment is carried out at atmospheric pressure and room temperature of 27 °C. The entire experimental setup was closed to prevent air flow. In the present numerical model, impingement of droplet is not considered. In order to approximate the same in the experimental setup the droplet is gently placed at the heated plate with a syringe controlled by a microcontroller. The control method is presented in [10]. The line sketch of the model with heated plate, enclosure and droplet is shown in Figure 1. Here temperature of enclosure refers to the average

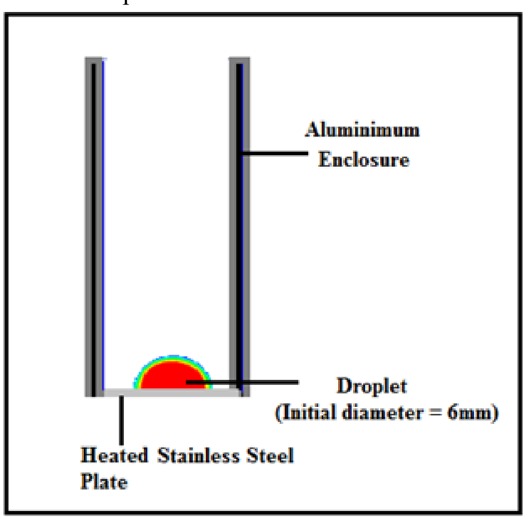


**Figure 1.** Line sketch of the Evaporation in Enclosure

## NUMERICAL MODEL

In the present work, a virtual liquid droplet is assumed to be at the centre of the enclosure on the heated plate as shown in Figure 1 which resembles a semicircle in 2-D. Numerical modelling is done using commercial finite volume code ANSYS FLUENT © in 2-D environment. 2-D modelling is used as the area of interest was to study the effect of surface roughness on the plane passing through the centre of the droplet. Multiphase modelling is done using Volume Of Fluids (VOF) method [11]. The present model is limited to the study of the droplet lying on the heated surface without considering impingement. This allows characterization of droplet due to evaporation alone neglecting transient dynamics due to impingement. The geometry and ambient conditions for the numerical model is the same as that given in the experiment. Theoretical droplet diameter of 6mm is simulated with water as fluid. The numerical model is discretised with rectangular elements of fine sizing. Grid independency study as shown in Figure. 2 is used to arrive at the optimal meshing size. A total of 53232 elements were used in the present models. Spray systems usually produce fine droplets of the order of few hundreds to few thousand microns. The present work corresponds to the droplets produced by quench spraying systems where the droplet size is as large as few mm [12]. There is no external flow rate/. The properties of water and vapour used are shown in Table 1 and 2. In the Volume of Fluids Method, three equations govern the study of the evaporation process. The continuity and Navier-Stokes shown in equation 1 and equation 2 are coupled with energy equation. Shown in equation 3.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \left[ \mu \left( \nabla \vec{v} + \nabla \vec{v}^T \right) \right] + \rho \vec{g} + \vec{F} \tag{2}$$

Here 'v' and 'ρ' represent the velocity and density of the mixture. 'F' is the surface tension acting on the mixture. The solver also solves a set of momentum equations to give the volume fractions of all the different phases as shown in equation 3. Equation 4 shows the transient modelling of change in volume fraction. The transport equation is solved for each phase as shown for one phase and the interface is determined at every time step. Here $k_{eff}$ is the effective thermal conductivity of the medium and E is the energy.

$$\frac{\partial}{\partial t}(\rho E) + \nabla . (\vec{v}(\rho E + p)) = \nabla . (k_{eff} \nabla T) \tag{3}$$

$$\frac{\partial (\alpha_q)}{\partial t} + \nabla \cdot (\alpha_q \vec{v}_q) = 0 \tag{4}$$

Where $\alpha_q$ is the volume fraction at the qth phase (i.e) all values of $\alpha_q$ between 0 and 1, there is a vapour-liquid interface while for values of 0 and 1, one phase is non-existent. The sum of volume fractions is always unity in accordance with the multiphase physics and is given by equation 5.

$$\sum_{q=1}^{n} \alpha_q = 1 \tag{5}$$

The Continuum Surface Force model is used as the surface tension model in FLUENT (Equation 6). Calculation of curvature κ in the interface is described by

$$\kappa = \frac{1}{|n|}\left(\left(\frac{n}{|n|}\nabla\right)|n| - \nabla . n\right) \tag{6}$$

Where the unit normal vector n to the interface is given by:

$$n = \nabla \alpha$$

$$F = \frac{\rho\sigma\kappa\nabla\alpha}{(\rho_1 + \rho_2)/2} \tag{7}$$

Where F is the surface tension force applied to computational cells with volume fraction between 0 and 1. The wall surface roughness is taken to be constant in both, the heated plate and walls of the enclosure. The numerical model is validated with the experimental results in terms of the wall contact angle made with the horizontal plate and the vertical surface during the droplet evaporation. Contact angle $\alpha_h$ (Alpha H) which is the angle made with surface of the droplet and the heated surface is conventionally defined. However in the present work there is an additional contact angle $\alpha_v$ (Alpha V) that is defined as the angle made by the surface of the droplet with the walls of the enclosure. Hence the value of $\alpha_v$ is defined only when the spreading radius equals the width of the enclosure and $\alpha_h$ is defined when spreading radius is less than the width of the enclosure. The corresponding values are calculated from experiments using the algorithm mentioned in [9]. Figure 3 shows the validation plot from which one can see that there is a good coincidence between the numerical and experimental result. The validation is done for a plate with average surface roughness of 0.2068 millimetres. The law-of-the-wall for mean velocity modified for roughness is used in the present work. The law can be expressed as shown in equation 8.

$$\frac{u_p u^*}{\tau_w/\rho} = \frac{1}{\kappa}\ln\left(E\,\frac{\rho u^* y_p}{\mu}\right) - \Delta B \tag{8}$$

The definition of the variable used and the various turbulence regimes existing corresponding to various surface roughness is shown in [13]. In the present work roughness constant is varied between 0.5 -0.8 and roughness height is varied from 0.1 to 1.5 mm.

**Table 1 Properties of water in liquid phase**

| Description | Water |
|---|---|
| Density(kg m-3) | 1000 |
| Specific Heat (J/Kg C) | 4182 |
| Thermal Conductivity(W/m K) | 0.6 |
| Viscosity(Pa s) | 0.0009 |

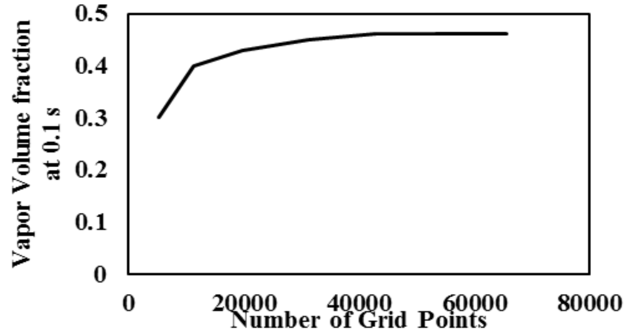


**Figure 2** Grid independency study

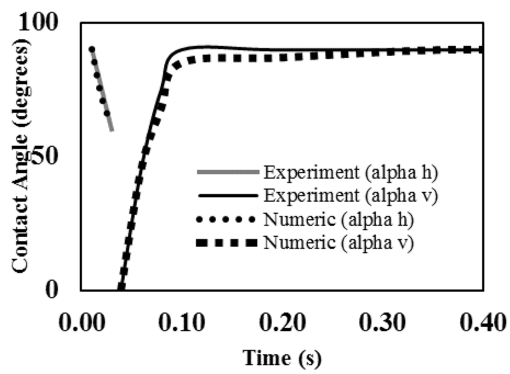


**Figure 3** Validation

**Table 2 Properties of water in Vapour phase**

| Description | Water |
|---|---|
| Density(kg/ m3) | 0.5542 |
| Specific Heat (J/Kg C) | 2014 |
| Thermal Conductivity(W/m K) | 0.0261 |
| Viscosity(Pa s) | 1.34e-05 |

## RESULTS AND DISCUSSION

### Effect of Enclosure

Initially droplet dynamics is studied on the heated stainless steel plate without the presence of enclosure and the variation in energy absorbed by the droplet is studied in the absence of enclosure. It was seen that as the droplet evaporates, it absorbs considerable amount of energy from the base plate leading to a decrease in temperature. The droplet spreads and shrinks as presented in [9]. The droplet loses the absorbed energy as it spreads. This causes a pressure gradient towards the centre of the droplet that in turn causes shrinkage of the droplet. As the droplet shrinks, there is a sudden increase in the amount of energy absorbed leading to an increased heat transfer. However the droplet vaporizes soon following the shrinkage. Thus the increased heat transfer rate is short lived. Figure 4 provides a summary for this in the form of a graph.

With the introduction of the enclosure a clear difference is seen in the dynamics of the droplet. The energy absorbed by the droplet increases considerably leading to enhanced heat transfer from the base plate. The reason for the increase in energy absorbed by the droplet is the instantaneous transfer of heat from the heated plate to the enclosure walls. Thus the amount of heat transferred from the base plate to the walls is high leading to decreased base plate temperature. The amount of energy absorbed with time in the case of evaporation with and without enclosure is shown in Fig. 5. It can be clearly seen from the graph that the amount of energy absorbed is predominantly high in evaporation within enclosures than in open atmosphere at all the time intervals considered. Thus one can conclude that there is an enhanced evaporative cooling of heated plates when the evaporation happens within the enclosure as the droplet carries the heat and touches the enclosure thereby transferring it.

The phase fraction distribution or transient droplet dynamics is of same importance as the heat transfer characteristics explained in the preceding paragraphs. In the present case, the width of the wall enclosure is less than the spreading radius of the droplet. As explained earlier there are two contact angles; one with vertical and other with horizontal. The horizontal contact angle decreases and the vertical contact angle increases as shown in Figure 3.

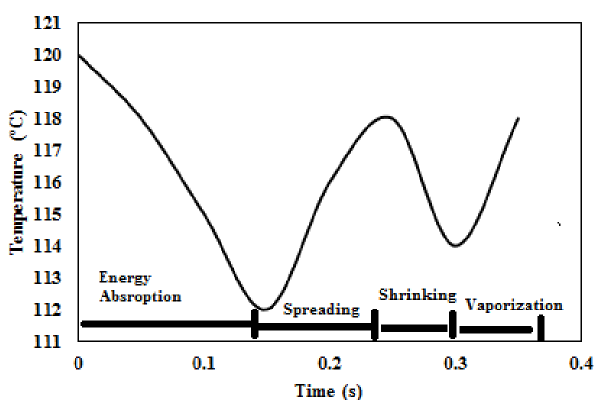


**Figure 4.** Variation in base plate temperature during droplet evaporation

The reason for this can be explained by closely inspecting the droplet dynamics in terms of the spreading radius. The spreading radius of the droplet increases as heat is supplied to the droplet. As the spreading radius increases and reaches the width of the wall, the water level along the vertical wall increases. This causes an increase in vertical wall contact angle. It is observed that the water deposition increases along both the wall directions. This can be reasoned by considering the zone of high temperature. The applied temperature is high in the middle part of the enclosure. Thus, there is thermal agitation in the droplet causing high water concentration along the enclosure walls. But as the wall temperature raises the total pressure along the enclosure walls, droplet accumulation over the walls increases and the central region of the enclosure faces reduction in pressure. As a result of pressure gradient, the droplet accumulated on the walls of the enclosure moves towards the low pressure region. This leads to a wave-like formation at the centre of the enclosure and the droplet rises up. As the droplet rises up, a resulting pressure gradient is again experienced along the height, which is also induced by the change in temperature. This leads to more diffusion of droplet particles into the atmosphere. The entire process is shown in Figure 6.

**Effect of Wall surface roughness.**

Surface roughness is important in the evaporation of droplet over heated plate. However, its effect is important in the case of enclosures as there is an increased area of contact for the droplets. In the present work, analysis has been carried out to study the dependence of droplet dynamics on the wall surface roughness. The present work provides the preliminary analysis on the effect of wall surface roughness. Thus the roughness of the stainless steel plate and the aluminium enclosure is considered the same in the numerical analysis to reduce the complexity. It is seen from the analysis that the effect of surface roughness force becomes significant with the introduction of the enclosure. Figure 6 shows the detailed comparison of the initial stages of droplet evaporation. As the water droplet moves, the meniscus of the droplet changes dynamically thus giving various contact angles. Moreover, the droplet reaches equilibrium in certain time period after which there is too little change in contact angles. Beyond the equilibrium time, the droplet erupts from the centre of the droplet as a result of evaporation favoured by differential pressure gradient at the centre of the droplet.

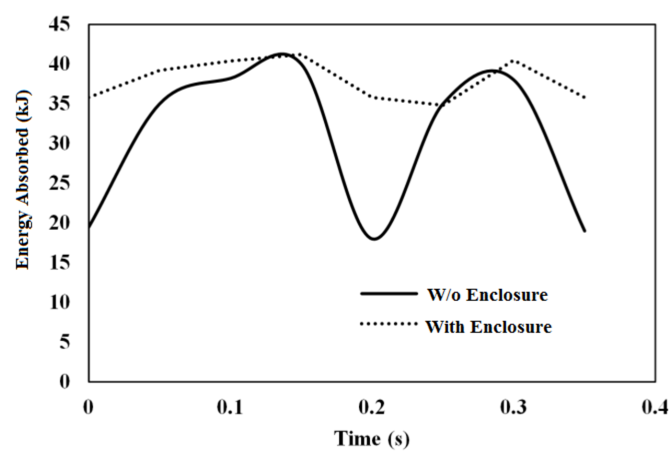


**Figure 5** Energy absorbed by the droplet during evaporation

It can be seen that in the absence of surface roughness, the pressure gradient due to inertia becomes predominant and causes a wavy nature and the droplet flows back from the concentrated water zones on the vertical wall. However in the presence of surface roughness, the roughness dominates and the pressure gradient is at a minimum. Hence, the formation of depression at the centre of the enclosure is prevented and the surface of the water droplet becomes considerably flat. Thus there is no differential pressure gradient along the width of the enclosure. This leads to a constant heat transfer rate when compared to evaporation happening in the absence of surface roughness.

As the surface roughness (roughness height) increases, the height of droplet accumulation on the walls of the enclosure increases. This leads to higher absorption of energy from the heated plate to the enclosure wall when the roughness of the enclosure is quite high. The maximum height of droplet along the width of the enclosure as the droplet reaches equilibrium is shown in Figure 7 for various surface roughness values. It can be seen from the figure that, as the surface roughness (roughness height) increases, there is a marked increase in the maximum height of water accumulation. Moreover, with increase in surface roughness, the maximum height along the spatial direction is uniform. However, it can be seen that for evaporation in a surface with low roughness, the maximum height of accumulation is higher at the walls; it gradually reduces at the centre. This can again be reasoned considering the predominance of surface roughness compared to the inertial forces.

The transient nature of droplet dynamics is also found to be influenced by the surface roughness of the metal. It is seen from the analysis that the spreading time is not influenced greatly by the surface roughness. However, time to reach the maximum height and to attain the flat top surface is affected by surface roughness. In order to quantify this, the contact angle plot with time is plotted in Figure 8 for different surface roughness of metal surfaces.

It can be seen that there is less difference in the characteristics of $\alpha_h$, the horizontal contact angle. This shows that the horizontal spreading time of droplet is independent of surface roughness. However the value of $\alpha_v$ increases and reaches a constant value in a small time duration when the surface roughness value is high. This indicates that surface roughness plays a major role coupled with time which is accompanied by the decreasing effect of inertia. One needs to obtain a concrete insight into the role of surface roughness on the droplet dynamics and heat transfer characteristics for evaporation inside an enclosure. Future work is aimed at arriving at a numerical correlation for the same and extension of the work to phase change and porous material based substrate.

## CONCLUSION

Experimental and numerical analysis has been done in the present work to arrive at a physical understanding of evaporation of a single water droplet in a rectangular enclosure. The enhanced cooling effect of the heated plate because of droplet evaporation is described and evaporation in the presence of a closed chamber is found to provide an enhanced cooling effect. The analysis has been extended to study the role of surface roughness on the droplet evaporation in the enclosure. It was seen that with the increase in surface roughness, the time for vertical spreading decreased and a near flat surface was formed on the top contrary the wavy nature obtained in the absence of surface roughness. This led to a change in contact angle variation with time which in turn affected the heat transfer characteristics. The conclusion reached is that with increase in time, the effect of surface roughness is more predominant than inertial effects.

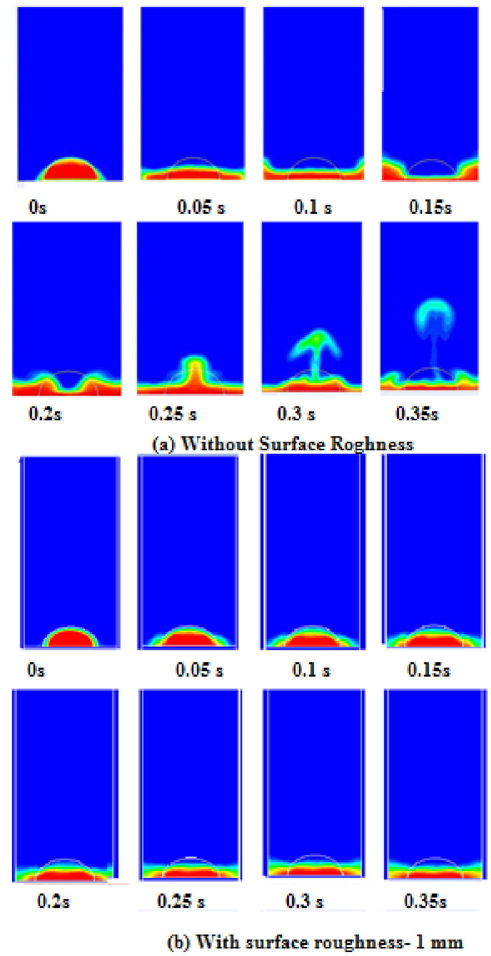


**Figure 6** Phase fraction distribution of droplet during evaporation

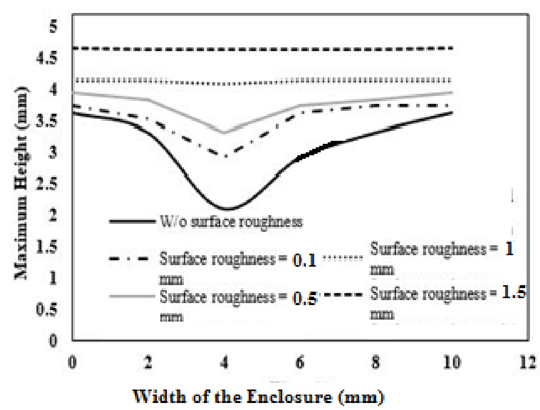


**Figure 7** Effect of surface roughness on Height of water accumulation

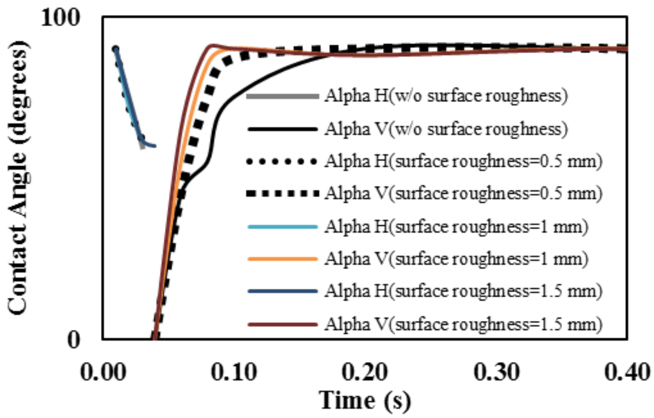


Figure 8 Effect of surface roughness on contact angle variations

## REFERENCES


[1] Z. Tamura, Y. Tanasawa; Evaporation and Combustion of a Drop Contacting with a Hot Surface. 7th Symposium (International) on Combustion, Butterworth's Scientific Publications, London (1959)

[2] Hubbard, G., Denny, V., and Mills, A., "Droplet evaporation: effects of transients and variable properties". International Journal of Heat and Mass Transfer, 1975. 18(9): pp. 1003-1008.

[3] Bernardin, J.D., Mudawar, I., Walsh, C.B., and Franses, E.I., "Contact angle temperature dependence for water droplets on practical aluminum surfaces". International Journal of Heat and Mass Transfer, 1997. 40(5): pp. 1017-1033.

[4] Zeoli, Nicola, Sai Gu, and Spyros Kamnis. "Numerical modelling of metal droplet cooling and solidification." International Journal of Heat and Mass Transfer 51, no. 15 (2008): 4121-4131.

[5] Wachters, L. H. J., and N. A. J. Westerling. "The heat transfer from a hot wall to impinging water drops in the spheroidal state." Chemical Engineering Science 21, no. 11 (1966): 1047-1056.

[6]. Kurokawa, M., and S. Toda. "Heat transfer of an impacted single droplet on the wall." In Proc. ASME/JSME Therm. Eng. Joint Conf, vol. 2, pp. 141-146. 1991.

[7]. Xiong, T. Y., and M. C. Yuen. "Evaporation of a liquid droplet on a hot plate."International journal of heat and mass transfer 34, no. 7 (1991): 1881-1894.

[8]. Di Marzo, Marino, and David D. Evans. Evaporation of a water droplet deposited on a hot high thermal conductivity solid surface. National Bureau of Standards, 1986.

[9] . Reddy, V. Harshavardhan, Shaik Sadiq, S. Arunkumar, and M. Venkatesan. "Investigation of Single Water Droplet Evaporation over Aluminium Surfaces Using High Speed Camera and Image Processing." In Applied Mechanics and Materials, vol. 592, pp. 1642-1646. 2014.

[10] Appaji, M.S.V., Reddy, G.S., Arunkumar, S. and Venkatesan, M., 2014. An 8051 Microcontroller based Syringe Pump Control System for Surface Micromachining. Procedia Materials Science, 5, pp.1791-1800.

[11] Hirt, Cyril W., and Billy D. Nichols. "Volume of fluid (VOF) method for the dynamics of free boundaries." Journal of computational physics 39.1 (1981): 201-225.

[12] Viswanathan, R., Gandy, D., & Coleman, K. (Eds.). (2005). Advances in Materials Technology for Fossil Power Plants: Proceedings from the Fourth International Conference, October 25-28, 2004, Hilton Head Island, South Carolina (Vol. 1011381). ASM International.

[13] Fluent, Ansys. "12.0 Theory Guide." Ansys Inc 5 (2009).