Numerical Study of Condensation Heat Transfer and Droplet Dynamics on Different Wetting Surfaces of Gas Transportation Pipelines

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Abstract
In this work, numerical investigation of condensation on a horizontal pipe which has various wettability properties analyzed. The influence of droplet size and contact angle on the performance of heat transfer is investigated. The condensation heat transfer obtained using MATLAB software to find the optimum function that enhances the performance. The wetting behavior is discussed under the atmospheric condition by considering the non-condensable gas. The effect of thermal boundary layers resulted from the droplet conduction, interfacial, coating, non-condensable gas, convection heat transfer was considered as well. The heat transfer rate is influenced by the droplet diameter for both hydrophilic and hydrophobic surfaces. The heat transfer rate increased by 30% when the droplet diameter is 1.5 mm than the droplet diameter is 2.5mm. The contact angle has affected the performance of heat transfer on hydrophilic surfaces.

Keywords: condensation, hydrophilic, hydrophobic, droplet diameter, contact angle, heat transfer rate.

1. Introduction

Condensation is a complex process of converting a substance from a vapor phase to a liquid phase. It results when the temperature of a condensing surface is lowered below the saturation temperature of the surrounding vapor or the vapor pressure of the material is increased above saturation values [1]. The liquid phase formation can be controlled by two key parameters, i.e. the temperature and the wetting properties of the condensation surface. These two parameters
control the nucleation rate and growth of droplet patterns. Condensation at the pipeline is classified into two regimes: filmwise condensation and dropwise condensation.

When transporting wet gas that is produced from oilfields, due to significant heat exchange between the inside of the pipe and the outside environment, condensation of water vapor carried by the wet gas occurs on the internal pipe wall. Typically, the condensed water is pure and, due to the hydration of CO₂ which is generally present in oil and gas, the condensed water becomes more acidic and has a pH value of approximately 3.8, this leads to severe internal corrosion[1]. Error! Reference source not found. shows the condensation process at the gas pipeline during wet gas transportation.

![Condensation process](image)

Figure 1 schematic of the liquid condensation processes inside the gas pipeline.

Unlimited developments are proceeding to enhance condensation heat transfer rate and droplet dynamics on wetting surfaces. Regard to condensation on hybrid surfaces, the surface wetting has a significant influence on droplets departure frequency and heat transfer performance because it affects the thermal boundary layers and droplets growth rates. The wetting behaviors depend mainly on contact angles and droplet sizes [2]–[6]. The surfaces can be classified into hydrophilic, hydrophobic and superhydrophobic according to the contact angle values [7]–[10]. Therefore, the research on optimizing the durable condensation surfaces still in progress. Numerous methods have been achieved to enhance condensation heat transfer. Changing the geometry of the condensing surfaces has an important effect on the enhancement of heat transfer for condensation because it increases the condensing’s surface area and improves droplet’s dynamics. A horizontal copper tube that is wrapped with steel wires that have various diameters and different pitches as well were tested under condensation heat transfer conditions for various
types of steam [11], [12]. The enhancement ratio was 3 for R113 and 2 for ethylene glycol and steam compared to plain surface. The convective heat transfer rate and condensation in a polymer plate heat exchanger were enhanced by adapting the geometry using polymer inserts [13]. The heat transfer rate increases by 90% compared to the heat transfer for a plate without inserts. The increase in the heat transfer rate was due to increase the convection surface area and increase the disturbance caused by the inserts where the droplets are sticking to them and roll off from the surface. Condensation heat transfer on horizontal copper tubes which wrapped using round copper wires and square wires of copper and brass materials were studied experimentally [14]. The effect of wire’s dimensions, the material of the wire, and the pitches are investigated. The heat transfer rate of a copper tube wrapped with copper square wires is higher than copper tube wrapped with brass square wire because of the effect of thermal conductivity differences. The enhancement of heat transfer rate for 0.8mm length of square wire is lower than 0.8mm wire diameter, but the improvement of heat transfer rate for 1mm length of square wire is higher than 1 mm wire diameter. The higher heat transfer was obtained when the pitch is 4mm, but the heat transfer decreases with further increasing of pitch’s dimensions because of less active of the tube’s surface area. Adding grooves on condensing surfaces can enhance condensation heat transfer [15]. The behavior of falling droplets is improved where the droplets sweep frequently from the surface when the grooves distributed vertically, and the heat transfer enhanced. The horizontal groove’s distributions work as a resistance against falling the droplets down and reduce the heat transfer rate.

Condensate droplets can sweep spontaneously away on the superhydrophobic surfaces but not on other superhydrophobic surfaces [16]. Four superhydrophobic surfaces with different nanostructures have been examined to figure out droplet motion during condensation in the ambient environment. The only surface with small roughness makes the movement of condensate droplets easier with high mobility. The droplet movement depends on the relative humidity in the condensation environment. The surface tension force is larger than the interaction force between the solid surface and condensate water in some superhydrophobic surfaces. Therefore, this surface tension leads to a significant decreasing in droplet motion caused by the slower nucleation, growing velocity, and coalescence probability due to the low relative humidity. A theoretical model developed [17] to study the condensation and droplet jumping during on superhydrophobic flat plate. The influence of the jumped droplet sizes, the
plate inclination, and the steam velocity was described. The jumping of droplets can destroy the thermal boundary layers and improve the performance of condensation. The droplet’s size and the droplet’s jumping height are important factors that affect condensation improvement.

The plate orientation influences the droplets jumping height in the way the droplet The effect of surface energy and nanostructure on dropwise condensation heat transfer have been experimentally studied [18]. The heat transfer rate for a smooth surface with SAM is higher than the nanostructure surface with SAM. The heat transfer rate for the smooth surface is enhanced by a factor 3 compared to filmwise while the heat transfer rate with nanostructure surface is also enhanced the heat transfer by a factor 1.8. The condensate’s droplets fill the cavities between the structures and create a film on the condensation surface that reduces condensation heat transfer. Then, the difference in free energy between the surface and liquid will decrease, and the apparent contact angle hysteresis will be significant. Hydrophobic polymer surfaces have the same surface energy, but the roughness and contact angle hysteresis are different have been analyzed during dropwise condensation [19]. The increase in surface roughness and contact angle hysteresis plays an important factor for enhancing the heat transfer rate for condensation because it increases the number of nucleation sites and droplet growth rate. The influence of the condensation environment on surface wettability has been explained [20]. The surfaces (bare copper and copper coated with SU-8) which have the same wettability in ambient conditions present deferent wetting behavior and growth of droplets in the condensation environment. The copper surface with SU-8 coating has low surface energy in the condensation environment and has a high heat transfer rate compared to bare copper.

Condensation heat transfer efficiency can be promoted using hybrid surfaces since a quickly removing for the condensate’s steam happens during the phase transition process, and the size of droplets on the condensing surface minimizes. A good improving heat transfer rate by implementing hydrophilic-hydrophobic vertical stripes [21]–[24]has been fabricated. The heat transfer rate was higher compared to complete dropwise condensation. The maximum width of the hydrophilic and hydrophobic regions was found to increase the heat transfer rate. Also, condensation on hybrid surface circular pattern outcomes the performance of the dropwise surface because of reducing flooding effect and increasing droplet departure frequency [25]. The heat transfer rate increases by 79% compared to the complete dropwise surface.
In this work, numerical investigation of condensation on a horizontal tube which has various wettability properties analyzed. The influence of droplet size and contact angle on the performance of heat transfer is obtained. The condensation heat transfer obtained using MATLAB software to find the optimum function that enhances the performance. The wetting behavior is discussed under the atmospheric condition by considering the non-condensable gas. The effect of thermal boundary layers resulted from the droplet conduction, interfacial, coating, non-condensable gas, convection heat transfer was considered as well.

2. Mathematical Modeling

The prediction of heat transfer performance of condensation begins by providing an expression for heat transfer through a single droplet. The analysis can be obtained by considering all thermal resistances in the direction of heat from saturated vapor to solid surface. The expression was determined by [26] which includes the effect of surface wettability level that is measured by the droplet contact angle. The surface with a droplet contact angle equal to or larger than 90° is called hydrophobic, while the droplet contact angle is less than 90°, the surface is called hydrophilic. The temperature droplet due to liquid-vapor interfacial resistance is given by [26].

\[ \Delta T_l = \frac{q_d}{2h_{pr}r^2(1 - \cos \theta)} \]  

1

The coating resistance provides an additional thermal boundary layer on the condensing surface and can be expressed as:

\[ \Delta T_{coating} = \frac{q_d \delta}{k_{coating}r^2 \ln^2 \theta} \]  

2

The thermal resistance of droplet curvature is [3]

\[ \Delta T_c = \frac{2T_{sat} \sigma}{h_f \rho r^2 \rho} \]  

3

The minimum drop radius which is smallest thermodynamically viable drop [1],[14]
Therefore, the thermal resistance of droplet curvature becomes

\[ \Delta T_c = \frac{r_{min}}{r} \Delta T \]  

The resistance of conduction through a single droplet is

\[ \Delta T_{droplet} = \frac{q_d \theta}{4\pi r k_c \sin \theta} \]  

Then, the expression for heat transfer rate through single droplet is [26]

\[ q_d = \frac{\Delta T r^2}{\delta k_{coating} \sin^2 \theta \left( \frac{r g}{4k_c \sin \theta} \frac{1}{2h(1-\cos \theta)} \right)} \]  

The heat transfer expression of a single droplet depends on the droplet size and contact angle. The total temperature droplet \( \Delta T \) is the difference between saturated vapor temperature to solid surface temperature. The heat flux increases in case of small droplet size because the droplet volume decreases which reduces the conduction resistance. Therefore, the condensation heat transfer performance will be improved when small droplets nucleate on the condensation surface [6]. In addition, the heat transfer rates decrease with a decrease in the droplet contact angle due to reducing the liquid-vapor interfacial and conduction resistances.

The maximum droplet radius is expressed in Equation 8 [22] is obtained by the force balance of interfacial and gravitational forces on a droplet with respect to contact angle hysteresis.

\[ r_{max} = \left[ \frac{3k \rho (\cos(\theta_r - \theta_a) \sin \theta)}{\pi \sin \theta (2 - 3 \cos \theta + \cos^2 \theta) \rho g} \right]^{1/2} \]  

The contact angle hysteresis is the difference between the advancing \( \theta_a \) and receding \( \theta_r \) contact angles. The value of \( k \) is a numerical constant that depends on the shape of the contact surface between a droplet and a solid surface. To obtain the expression for the total heat transfer through all droplets, one must integrate over the total number of droplets and the whole size distribution of the droplets. It is important to know the minimum, maximum radius and the
radius that droplets coalesce and swept from condensing surface. So, to obtain total heat flux during dropwise condensation [26]:

$$Q = \int_{r_{min}}^{r_e} q(r) n(r) \, dr + \int_{r_e}^{r_{max}} q(r) N(r) \, dr$$  \hspace{1cm} (9)

Where,

$$n(r), N(r)$$ the population density of small and large droplets

$$r_e = \text{radius where the drop coalescence and swept.}$$

2.1 Droplet size distribution

In the condensation process, small droplets start to nucleate on the surface and they grow in size by direct condensation. As the growth rate process continues, the spacing between droplets becomes small until they start to merge and grow by coalescence. In the droplet growth of generation droplets, a new generation is formed on the area not occupied by the previous generation [26] and the expression for droplet size distribution is obtained.

$$N(r) = \frac{1}{3\pi r^{2}}$$  \hspace{1cm} (10)

Small droplets grow during dropwise condensation from the smallest radius at which coalescence then sweep through different size. The growth rate for a drop is defined as [26]:

$$G = \frac{dr}{dt}$$  \hspace{1cm} (11)

By making several drops balances in size range $$r_1$$ to $$r_2$$ where the number of droplets entering = number of drop leaving + number of drop swept.

$$\frac{dr}{dt} = G = \frac{2 \Delta T_t}{\rho H_f g} \left( \frac{1 - \frac{r_{min}}{r}}{\delta(1+\cos \theta)} \frac{\frac{2}{r} - \frac{r_{max}}{r} - \frac{L_p}{r^2}}{k_p(1-\cos \theta)} \right)$$  \hspace{1cm} (12)

$$\frac{dG}{dr} = \frac{2 \Delta T_t}{\rho H_f g} \left[ \frac{\left(\frac{2}{r} + \frac{L_p}{r^2}\right) - \left(r - r_{min}\right) \left(\frac{2}{r} + \frac{L_p}{r^2}\right)}{r^2 + \frac{2L_p}{r^2} + \frac{L_p^2}{r^4}} \right]$$  \hspace{1cm} (13)

After applying boundary conditions, we obtain:
\[ n(r) = N(r) \quad \text{at} \quad r = r_e \]

\[
n(r) = \frac{r_{\text{max}}^{2/3} r (r_e-r_{\text{min}}) (r_e^2 r + \frac{2}{h_1} t_p)}{3\pi r_e^{5/3} t_{\text{max}} (r-r_{\text{min}}) (r_e^2 r + \frac{2}{h_1} t_p)} \exp(D_1 + D_2) \]

Where,

\[
D_1 = \frac{\rho H_f g}{2 k \Delta T} \left[ \frac{r_e^2 - r^2}{2} + r_{\text{min}} (r_e - r) + r_{\text{min}}^2 \ln \left( \frac{r_e - r_{\text{min}}}{r - r_{\text{min}}} \right) \right] \]

\[
D_2 = \frac{\rho H_f g}{2 k \Delta T} \left[ \frac{r_e^2 - r^2}{2} + r_{\text{min}} (r_e - r) + r_{\text{min}}^2 \ln \left( \frac{r_e - r_{\text{min}}}{r - r_{\text{min}}} \right) \right] \]

\[ r_e = \text{the radius at the boundary between the coalescence and the non-coalescence size.} \]

\[
r_e = \sqrt{\frac{1}{N_s}} \]

\[ N_s = \text{the number of nucleation sites density on the condensing surface.} \]

The heat flux can be calculated from the heat transfer through the drops and the drop size distribution with including time drop growth from \( r_{\text{min}} \) to \( r_{\text{max}} \).

\[
Q = \int_{r_{\text{min}}}^{r_e} q(r) n(r) \, dr + \int_{r_e}^{r_{\text{max}}} q(r) N(r) \, dr \]

Where the \( \frac{dr}{dt} \) is the drop growth rate.

\[
N(r) = \frac{r_{\text{max}}^{2/3}}{3\pi r_e^2 r_{\text{max}}} \]

Where \( N(r) = \text{large droplets population density} \).

### 2.2 Model Validation

The corresponding importance of study condensation performance on hydrophilic and hydrophobic surfaces at various droplet’s diameter and contact angles are investigated. The present model predictions are compared with published theoretical and experimental results for heat transfer [24], [26]. Figure 2 shows the heat transfer results of the presented model compared with experimental results. The condensation surface is completely hydrophobic when the droplet
contact angle is 90°, the heat transfer rate was calculated at different sub-cooling temperatures. It is obvious that the heat transfer calculations are good agreement with the other theoretical and experimental results which give more reliable and convinced calculations.

3. Results and Discussions

Numerical results regarding condensation heat transfer on hydrophilic surfaces which have different contact angle values. The performance of condensation is dramatically influenced by the droplet’s diameter and contact angle. Figure 3 shows the performance of condensation at different subcooling temperatures when the contact angle 50° and 70°. The droplet’s diameter on the surface contributes to controlling the condensation performance. The heat transfer rate increases with reducing the droplet’s diameter when the contact angle is 50° as shown in Figure 3a because the small droplet size can migrate quickly. Increase the droplet’s migration increases the droplet departure and reduces the thermal resistance that decreases the condensation efficiency. Also, the big droplet size leads to flood the condensation surfaces and prevent the new droplet to be nucleated and condensed. When the contact angle is 70°, the condensation performance increases as shown in Figure 3b. Increase the contact angle reduce the surface wettability which decreases the thermal resistance. The heat transfer increase with reducing the droplet’s diameter due to the decrease in the effect of thermal resistance of condensation.
Figure 3 (a) heat transfer rates for different droplet's diameter when the contact angle is 50° (b) heat transfer rates for different droplet's diameter when the contact angle is 70°.

The condensation performance on the hydrophobic surface is shown in Figure 4. The effect of droplet diameter on the heat transfer rates can be noted. Small droplet size leads to high heat transfer performance because the small droplet size leads to reduce thermal resistance boundary layer thickness. Moreover, the hydrophobic surface has low wettability compared to the hydrophilic surface which enhances the droplet mobility and migration on the surface.

Figure 4 heat transfer rate for the hydrophobic surface at different droplet diameter.
4. Conclusions

Condensation is more favorable in terms of heat transfer characteristics because of needs in energy and water harvesting applications. Calculations of heat transfer performance for hydrophilic and hydrophobic surfaces are performed which requires the determination of heat transfer through the single droplet, drop maximum radius and droplet size distribution. It is concluded that the heat transfer is influenced by droplet diameter for both hydrophilic and hydrophobic surfaces. The heat transfer rate increase by 30% on the hydrophobic surface when the droplet diameter is 1.5 mm than the droplet diameter is 2.5 mm. The contact angle affects the heat transfer on hydrophilic surfaces. It is noted that the heat transfer increased by 20% with an increase in the contact angle.

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