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Introduction and Basics of Condensation

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Harshit Bhavsar*

Assistant Professor, mechanical engineering, SAL Education, Gujarat. India

***Corresponding Author:** Harshit Bhavsar, Assistant Professor, mechanical engineering, SAL Education, Gujarat. India.

Abstract

To assess the distribution of droplet sizes on a flat plate during dropwise condensation, a droplet detection technique has been devised. By integrating an equation for the single droplet heat transfer rate with the droplet size distribution, dropwise condensation heat transfer can be modelled. This chapter provides a thorough introduction to the condensation process. Both boiling and condensation take place throughout the thermodynamic heat transfer process. This article contains information about homogeneous and heterogeneous drop-wise condensation. The drop-wise condensation mechanism has been described with a diagram. The figure shows several contact angles and the resistance provided in dropwise condensation are recognized. The relevance of the condensation process and certain fundamental applications have been discussed recently.

Nomenclature

As : Surface area, m2.
Cp : Specific heat, J/kg. °C.
d : Pipe diameter of the helical coil, m D : Helical coil diameter, m.
h : Condensation heat transfer coefficient, W/m2. °C.
i : Specific enthalpy, J/kg.
k : Thermal conductivity, W/m. °C.
L : helical coil length, m.
m. : Mass flow rate, kg/s.
P : Helical coil pitch, m.
Nu : Nusselt number, -.
Q : Heat transfer rate, W.
Re : Reynolds number, -.
q” : Heat flux, W/m2.
T : Temperature, °C.
μ : Dynamic viscosity, kg/m.s.
g : Dry saturated steam.
i : inner, inlet.

o : outer, outlet.
st : steam.

Introduction

Condensation is the change of phase from the vapour state to the liquid or solid state. Condensation plays a major part in the heat rejection corridor of the Rankine power cycle and the vapour contraction refrigeration cycle, which generally involves pure substances. Condensation is defined as the phase change from the vapor state to the liquid or the solid state and occurs when the temperature of the vapor is reduced below its achromatism temperature. Condensation is generally done by bringing the vapor into contact with a solid face whose temperature is below the achromatism temperature of the vapor. But condensation can also do on the free face of a liquid or indeed in gas when the temperature of the liquid or the gas to which the vapor is exposed is below the achromatism temperature. Two modes of condensation are known; videlicet, film-wise, in which the vapor condenses as a nonstop film on the essence face, and dropwise, in which the vapor condenses as drops in the form of parts of spheres. Great advances were made in the study of the condensation of brume, in both proposition and factual experimental knowledge, during the period from 1890 to 1930. With certain types of face active agents, the compacting face may be altered to produce dropwise condensation of the brume rather of the usual film-type condensation. With pure brume, it has been shown that heat transfer portions on the brume side can be increased from five- to ten-fold by using dropwise condensation.

Condensation on a solid surface is accompanied by a spectrum of flow mechanisms that are almost identical to those engaged in boiling. Drop condensation is therefore very similar to nucleate boiling whether it occurs on the bottom of a cooled horizontal plate or on a vertical surface. The misting up of windows or mirrors makes the phenomena most obvious. The main type of condensation found in most industrial settings is condensation films, which are created when the population of droplets grows significantly. It would be unnecessary to repeat the analysis for condensation flows given their near similarities to boiling flows. However, we go into further detail about one example, film condensation on a vertical surface, in the next section. Condensation occurs when the temperature of a vapor is reduced below its saturation temperature.

- Direct contact, dropwise, film, or homogenous condensation modes are available.
- The vapor's properties, such as whether it is a single component, a multi-component system with all condensable components, a multi-component system with non-condensable component(s), etc.
- System geometry, including planar surfaces on the inside and outside.

The most helpful classification is probably based on the manner of condensation, and those kinds of condensation are now defined.

Classification of Condensation

Homogeneous Condensation

When a vapour is sufficiently cooled below its saturation temperature to induce droplet nucleation, homogeneous condensation can occur. This can be done by mixing two vapour streams that are at different temperatures, cooling vapor-no condensable mixtures (creating fog in the atmosphere), or abruptly depressurizing a vapour. In reality, warm, humid air masses that ascend and cool cause adiabatic expansion, which leads to cloud formation in the atmosphere. According to classical nucleation theory, when droplets of critical radius r (i.e., droplets just large enough so that the pressure difference between their interior and exterior can balance the surface tension force) are produced at a significant number, homogeneous condensation takes place in a pure, supersaturated vapour.

$$r^* = \frac{2\sigma v_f}{\frac{R_u}{M} T_g \ln(P_g/P_{sat})}.$$

The rate of generation of droplets with radius r ∗ in a unit volume is.

$$\frac{dn}{dt} = N\frac{v_f}{v_g}\left(\frac{2\sigma}{\pi m}\right)^{1/2} \exp\left[-4\pi\sigma\frac{r^{*2}}{3\kappa_B T_g}\right],$$

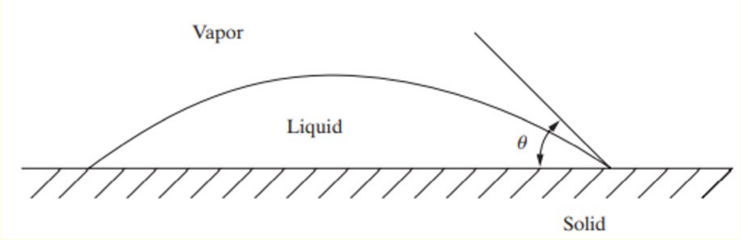

Figure 1: Condensation on a clean and dry surface.

Where T_g and P_g are the temperature and pressure of vapor, respectively, and N is the number density of

vapor molecules. Significant nucleation requires that $dn/dt \geq 10^{17}$-$10^{22} m^{-3} s^{-1}$.

While homogeneous nucleation in pure vapours is theoretically feasible, in reality dust and other particles serve as the embryos for droplet nucleation. In the atmosphere, fog formation usually relieves the supersaturation [defined as $\phi - 1$, where $\phi = P\nu / Psat(T)$ is the relative humidity], when supersaturation approaches a maximum value of about 1% (Friedlander, 2000). The droplets in fog have diameters in the 1-10 μm range.

Heterogeneous Condensation

In the vast majority of heterogeneous condensation processes, droplets develop on solid surfaces. When the surface is flat and dry, significant subcooling of the vapour is necessary for condensation to begin. Using kinetic theory, it is possible to describe the rate of formation of embryo droplets in heterogeneous condensation. According to this theory, dn/dt, the rate of generation of droplets with the critical size on a unit surface area of clean and dry surface (see Fig. 5. Carey, 1992).

$$\frac{dn''}{dt} = \left(\frac{2\sigma C}{\pi m}\right)^{1/2}\left(\frac{P_g}{\frac{R_u}{M}T_g}\right)^{5/3}(m^{-2/3})\cdot v_f C\frac{1-\cos\theta}{2}\exp\left[\frac{-16\pi\left\{\frac{\sigma C}{(R_u/M)T}\right\}^3 v_f^2}{3m\{\ln[P_g/P_{sat}]\}^2}\right]$$

According to this hypothesis, there must be a significant amount of surface subcooling for nucleation to take place at a sufficient number of locations. Condensation can start at low wall subcooling temperatures in reality, nevertheless, because surface impurities that are pre-existing nucleation embryos. Rapid condensation happens at significantly lower subcooling when liquid is found on surface fissures. There are many of hydrophilic oxides and corrosion products. These pollutants' absorbed water vapour molecules can act as condensation's starting points on metallic surfaces. Dropwise or film condensation modes may result from heterogeneous condensation.

Types of Condensation

In industrial equipment, condensation commonly results from contact between the vapor and a cool surface. This may occur in one of two ways:

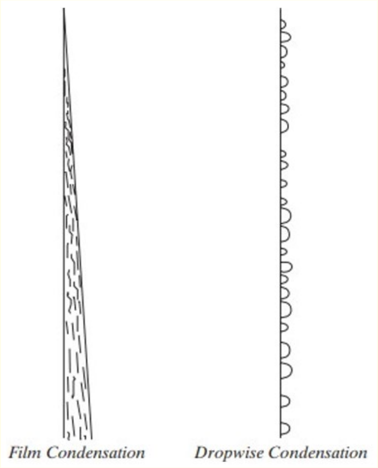

Figure 2: Film and Drop Condensation on Vertical Plate.

Filmwise condensation

The whole condensing surface is covered in a liquid film in this instance, and gravity is causing the film to continually flow away from the surface. This is typical of pristine, uncontaminated surfaces. In film condensation, the newly created condensate joins the liquid film that has already been formed on the surface, increasing the film thickness. When a liquid touches a surface, it condenses to form a continuous film that covers the area. This process is known as film condensation.

Dropwise condensation

In this instance, the liquid produces droplets on the surface rather than wetting it. This happens when a material that prevents wetness is applied to the surface. On the surface, the droplets develop in fissures, pits, and crevices. Typically, they move randomly around the surface. Film creation cannot maintain the high condensation and heat transmission rates that droplet formation can. Therefore, it is usual practice to replicate dropwise condensation employing surface coatings that prevent wetting. Maintaining dropwise condensation is frequently challenging. For these reasons, the assumption of film condensation is frequently used in condenser design calculations.

When the droplets in dropwise condensation reach a specific size, they slide down, cleaning the surface and exposing it to vapour. In this instance, there is no liquid coating to impede heat transmission. As a result, dropwise condensation has heat transmission rates that are more than ten times higher.

When a saturated, pure vapour comes into touch with a cold surface, such a copper tube, dropwise condensation takes place. The vapour condenses and may produce liquid droplets on the surface of the copper tubes. These droplets might not be attracted to the surface and instead of covering the tube, they would fall from it, leaving bare metal where further condensate droplets could develop.

Instead of forming a continuous film, dropwise condensation occurs when vapour comes into touch with a cooled surface, condenses, and produces individual droplets (Fig. 1). The newly created droplets expand by direct contact condensation on the droplet surface and coalescence with smaller adjacent droplets before being whisked away by gravity or vapour shear.

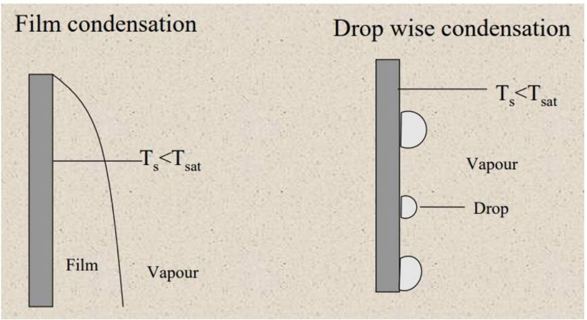

Figure 3: Dropwise and Film wise condensation image.

In dropwise condensation, the condensed vapour produces several droplets of varied sizes on the surface rather than a continuous sheet. As a result of ongoing condensation, the small droplets that form at the nucleation sites on the surface develop, coalesce into big droplets, and then slide down when they reach a particular size, clearing the surface and exposing it to vapour. This process is known as dropwise condensation. In order to produce dropwise condensation, a promoter chemical is added to the vapour, the surface is treated with the chemical, or the surface is coated with a polymer like Teflon or a noble metal like gold, silver, or platinum.

However, any gain in heat transfer must be weighed against the value related to sustaining dropwise condensation. one more reason for losing the effectiveness of dropwise condensation is that the accumulation of droplets on the condenser surface. the warmth transfer rate sharply decreases due to the accumulated droplets. Therefore, most condensers are designed on the idea that film condensation will happen on the surface.

One of the most efficient modes of heat transmission is called dropwise condensation, which is characterised by a high number of droplets of different sizes on the condensing surface as opposed to a continuous liquid sheet.

The total heat transfer by condensation to a surface of area A is calculated as follows:

$$q = \bar{h}_L A\left(T_{sat} - T_s\right)$$

The total condensation rate may be determined from the relation:

$$\dot{m} = \frac{q}{h'_{fg}} = \frac{\bar{h}_L A\left(T_{sat} - T_s\right)}{h'_{fg}}$$

Instead of heat transmission, nucleation is often the rate-limiting phase in both scenarios. The majority of industrial applications rely on film mechanisms since creating non-wetting surfaces is difficult and costly. Following condensation, the liquid slides downward down the tube surface due to gravity. Depending on the fluid, the rate of condensation, the size of the tube, etc., the flow may be laminar or turbulent. As the fluid flows to the tube's bottom, the film tends to become thicker, and ripples may emerge due to the fluid's weight. These will result in a departure from perfect laminar flow.

Because of phase change, when condensation happens, there is less vapour at the gas-liquid interface. As a result, the NCG builds up close to the gas-liquid contact, increasing thermal resistance. The condensation process' fundamentals for dropwise condensation are shown in Fig. 1. The vapour molecules are equally distributed throughout the surface of the droplet as it forms on the condensation surface, as illustrated in Fig. 1(a), and they encounter no resistance as they travel towards the gas-liquid interface.

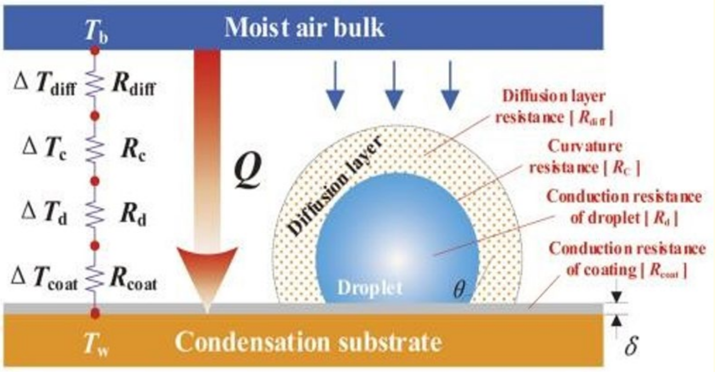

Figure 4: Schematic of the heat transfer model of dropwise condensation with NCG on a single droplet.

Since its discovery in 1930, dropwise condensation has sparked a lot of study interest since it has been shown to have up to an order of magnitude better heat transfer coefficients than film wise condensation (Fig. 4).

Mechanism of Dropwise Condensation

Due to the features of various surfaces, several condensation forms exist. Contrary to dropwise condensation, which results in tiny droplets, filmwise condensation leaves a continuous liquid film on the surface. A surface can be categorized as either a hydrophilic surface, a hydrophobic surface, or a superhydrophobic surface depending on how wet it is. Figure 1a depicts the droplet morphology on various surfaces. When the contact angle is less than 90 degrees, the surface is thought to be hydrophilic, while when the contact angle is greater than 90 degrees, the surface is thought to be hydrophobic and forms dropwise condensation [8]. The crucial angle established between the inclined surface and the horizontal surface when the droplet starts to roll off is represented by the rolling angle above. As shown in Figure 5b, the advancing and backward contact angles get bigger and smaller. Where the θa is the advancing contact angle, θr is the receding contact angle, and the Δθ = θa − θr is the contact angle hysteresis.

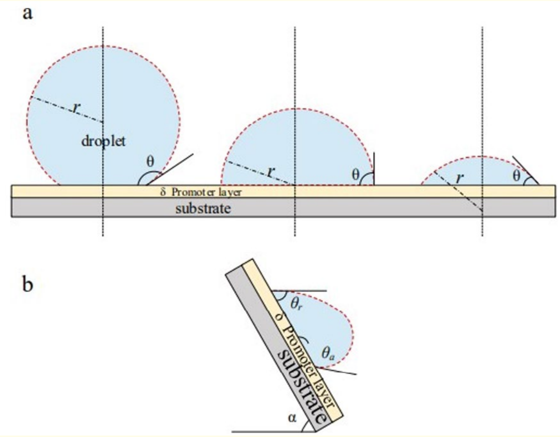

Figure 5: The contact angle of the droplets on the surfaces surface contact angle & advancing- receding contact angle (ref Davies, G.; Mojtehedi).

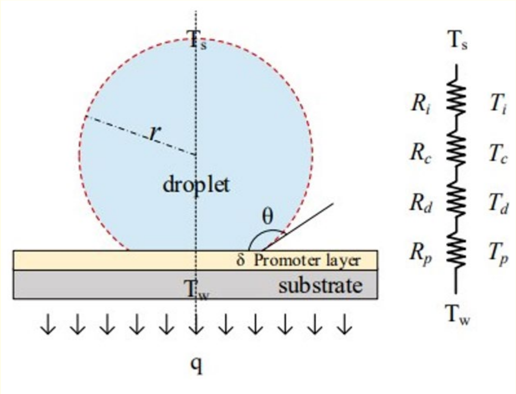

Figure 6: Schematic diagrams of the thermal resistance network of a single droplet.

Single Droplet Heat Transfer

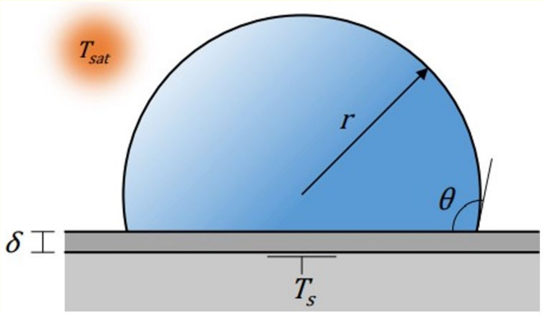

Figure 7: Condensate Droplet Model.

It is assumed that the condensate droplet has the shape of a spherical cap with radius r and contact angle. The coating is in thickness. Surface temperature Ts and saturation temperature Tsat are separated by the subcooling temperature T.

A number of models have been put out to describe how heat is transferred via a single droplet [1,2,22,23]. The subcool temperature T, which is the difference between Tsat and Ts in Figure 2, is defined by these models as four temperature dips between ambient conditions and the substrate. It is believed that the condensate droplet will resemble a spherical cap. These are the subcool temperature values for T.

$$\Delta T = \Delta Ti + \Delta Tcurv + \Delta Tdrop + \Delta Tcoa$$

Where ΔTi, $\Delta Tcurv$, $\Delta Tdrop$, and $\Delta Tcoat$ represent the temperature decreases across the liquid-steam interface caused by the curvature of the droplet, the droplet itself, and the coating, respectively. Kim and Kim [23] have found it analytically, in contrast to Fatica and Katz [22] who simulate $\Delta Tdrop$ via numerical integration. The latter approach is used to simulate the decline in temperature via the droplet.

The temperature drops in Equation.

$\Delta Ti = qd\ /\ hi2\pi r\ 2(1 - \cos\theta)$
$\Delta Tcurv = rmin\Delta T / r$
$\Delta Tdrop = qd\theta\ /4\pi rkc \sin\theta$
$\Delta Tcoat = qd\delta\ /kcoat\pi r\ 2 \sin 2$

Example & Applications of Condensation

Examples of Condensation:

- Making clouds by condensation.
- A layer of water around cold soft drink Glass.
- Drop a stick on the lead after boiling the Milk.
- Layer of water on the mirror in a very cold winter morning.
- In the Morning water drops appear on the Leaves.

Applications of Condensation

Power production, water desalination, thermal management, refrigeration, and air conditioning are just a few of the commercial applications of condensation that are used by both consumers and industry. Condensation polymerization is the method through which two or more monomers join together to create the polymer while getting rid of a tiny molecule.

Conclusion

As saturation temperature drops, the condensation heat transfer coefficient rises. The condensation heat transfer coefficient rises when pipe and helical coil diameters are reduced, then falls.

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