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Comparison of Heat Transfer Coefficients of Silver Coated and Chromium Coated Copper Tubes of Condenser in Dropwise Condensation

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ABSTRACT: *Since centuries steam is being used in power generating system. The steam leaving the power unit is reconverted into water in a condenser designed to transfer heat from the steam to the cooling water as rapidly and as efficiently as possible. The efficiency of condenser depends on rate of condensation and mode of condensation of steam in the condenser. The increase in efficiency of the condenser enhances the heat transfer co-efficient which in turn results in economic design of condenser and reduced pumping power for a desired output. Higher heat transfer coefficient in condensers is beneficial in the industrial applications e.g., Sugar industry, ships propulsion, nuclear power reactor, power generating system, production of Liquefied petroleum gases, liquid nitrogen and liquid oxygen. In the present experimental study, comparison of heat transfer coefficients of silver coated and chromium coated copper tubes of condenser have been performed. it has been observed that inside heat transfer coefficient (h_i), outside heat transfer coefficient (h_o) and overall heat transfer coefficient (U) associated with silver coated condenser made of copper is more than that of chromium coated condenser made of copper. It is also observed that all the three types of heat transfer coefficient increases with increase of steam pressure [1].*

Keywords: *Heat transfer coefficients, Condenser, Dropwise condensation, Heat transfer.*

I. INTRODUCTION

The heat transfer coefficient is defined as the proportionality constant between the heat flux and the thermodynamic driving force for the flow of heat i.e., the temperature difference, ΔT:

$$\mathbf{h = q/\Delta T}$$

where, q = amount of heat transferred (heat flux), W/m^2

i.e, $\mathbf{q = dQ/dA}$

h = heat transfer coefficient, W/m^{2}K and ΔT = difference in temperature between solid surface and rounding fluid area, K.

II. CONDENSATION

It is defined as phase change from vapour state to liquid state and occurs when the temperature of the vapour reduced below its saturation temperature. Condensation is classified into two groups; one is bulk condensation and the other is surface condensation. In bulk condensation vapour condenses in a gas phase. In surface condensation, vapour contacts with a surface having temperature below the saturation temperature of the vapour. There are a lot of applications with this type of condensation. Surface condensation is classified as film wise condensation and dropwise condensation.

Condensation is heat transfer process which attracted many researchers’ interests. Condensers for industrial applications are large in size and are very costly to manufacture. Enhancing the condensation heat transfer coefficient will have a great influence. Any progress will decrease the required power in pumping for desired output and thereby reduces the size of heat exchanger.

The two distinguishable ideal mode of condensation are: a). Film-wise Condensation, b). Drop-wise Condensation.

Drop Size Distribution:

Definition of geometry is essential for any heat transfer problem. It means that drop size distribution must be specified in dropwise condensation.

Based on high magnification visual observations, drops of varying diameters and different sizes are present on condensing surface. Coalescence of drops is the main cause of varying drop size when viewing a single spot on the surface. Fluctuation of condensing temperature is due to the different size of drops.

P. Griffith and C. Graham [2] measured distribution by a Polaroid microscope camera with a variety of magnifications. John W. Rose et al. [3] attempted calculation of heat transfer through a single drop of given size and concluded that distribution of drop size is not well understood.

Jacob [4] provided a basic understanding of mechanism of dropwise condensation and how a drop forms and grow. According to him on the condensing surface, a very thin layer of water or steam develops. When the certain thickness of layers is reached then there is a breaking of droplets occurs. As the layers are converted into droplets, it rolls down the condensing surface due to gravity. A new film immediately appears on the exposed area and thereby increases the heat transfer coefficient in DWC. Here condensation is taking place through thin film having low thermal resistance.

Tammann & Boehme [5] observed that there is existence of particular nucleation sites due to repetitive condensation and there is same arrangement on the surface while drops appear. Experimental study shows that there is nucleation sites and are randomly distributed due to which drops formation and growth occurs.

John W. Rose et al. [6] mainly concerned of particular small region of the condensing surface and theoretical distribution of drop size. The generation of largest drops decreases as it go down to the distance of the condensing surface. To determine the size distribution, it is very important to determine the largest drop on a location and then integrate it for whole condensing surface.

Yu-Ting Wu et al. [7] described a theoretical study on dropwise condensation. According to him on condensing surface repeatedly transient process occurs. With drop growth there is coalescence between the neighbouring drops. And due to which primary drops are formed at nucleation sites. Due to coalescence a sites is exposed and a new generation of drops formed. As the falling drops sweep the entire field, drops again grow and followed by third generation and process restarts. Random fractal model, dropsize and spatial distribution is stimulated by them. They captured the photograph of dropwise condensation at different instants. Based on investigation they suggested that these photographs are similar and enlargement of local photographs gives the whole photograph. The appearance of self-similar shown by dropwise condensation indicates the most important features of fractals.

Heat Transfer Through the Droplet

The amount of heat transfer through a single droplet is a function of its radius and size distribution over the condensation surface. As dropwise condensation occurs on the droplets of varying sizes, so amount of heat transfer through a single droplet must be calculated.

Variables affecting the dropwise condensation heat transfer are;

1). Surface Micro-properties
2). Steam Pressure
3). Surface Orientation
4). Steam Velocity
5). Promoter
6). Condenser Thermal Conductivity
7). Contact Angle

Peter Griffith and C. Graham [2] in their experimental analysis sum the heat transfer through all the drops on the surface using the dropsize distribution after evaluating the heat transfer through the single droplet. During their experimental analysis he assumed that there is no any bare space on condensing surface.

Fatica N and Katz D. L. [8] studied the heat transfer through a single droplet in dropwise condensation. In this he assumed that surface and base temperature of droplets are uniform & constant. Surface temperature of droplets is equal to vapour temperature and base temperature is equal to condensing surface temperature. Periphery of drop, triple interface between solid liquid and gas are the region where the majority of heat transfer takes place.

Sadhal et al. [9] studied the effect of solid properties and contact angle in dropwise condensation and evaporation. They investigate the effect of condenser material by utilizing the steady heat conduction equation for a spherical shape droplet on the solid condensing surface. Later he applied differential inequalities to find heat transfer through dropwise condensate. To obtain approximate solution they applied theory of differential inequalities. Upper and lower bounds for the exact solutions of the temperature distribution in droplets of arbitrary contact angle $0 \leq \theta \leq 90°$.

Tanner et al. [10] described that coefficient of heat transfer increases with an increase in steam velocity past the condensing surface. He investigated that dropwise condensation can be predicted by assuming that transfer of heat is through droplet by conduction.

Effect of Surface Finish on Dropwise Condensation

It is obvious look for any individual in dropwise condensation that a drop form, grows, combines together and finally rolls down along condensing surface.

Peter Griffith and C. Graham [3] investigate the surface and according to them it was observed that rougher the condensing surface, lower the coefficient of heat transfer while considering the roughness and wetting effect. Tiny scratches on mirror finish surface act as a favourable nucleation sites which keeps on producing the condensing drops. It is noticed that higher contact angle is required in dropwise condensation but due to roughness it decreases.

Peter Griffith et al. [11] studied the effect of contact resistance on different materials like copper and stainless steel. Contact resistance for condensing surfaces made up of stainless steel is approx. 4 times more than that of copper. Lower the thermal conductivity of material, lower the contact resistance. Due to the higher contact resistance, the heat transfer coefficient decreases in both dropwise and filmwise condensation processes.

Mechanism of Dropwise and Filmwise Condensation Process

Before discussing the coefficient of heat transfer in dropwise condensation, it will be appropriate to discuss various theories on the mechanism of dropwise condensation. Under the identical experimental conditions, it has been accepted by all the investigators that heat transfer coefficient in dropwise condensation is more than that in filmwise condensation.

In 1936 a theory was proposed by Jacob [3] and according to him the high heat transfer or condensation rate in dropwise condensation is due to a direct contact of the condensing surface with hot vapour/steam impinging upon it. The condensing vapour covers the cooling condensing surface and forms a thin layer of water which continuously and quickly grows in thickness until it forms droplets. This thickness varies from zero to certain value say δ. As the drops combine together and rolls downward off the surface making a portion of dry surface exposed to fresh steam and almost instantaneously covered by condensation of fresh steam. This process repeats itself and makes it a continuous process. The average thickness of this layer depends upon the condensing surface and slightly on rate of cooling. For the higher cooling rate, drops are developed in shorter interval of time. Higher cooling rate is obtained by using a high vapour to surface temperature.

Consider a surface in contact with vapour and maintained at a lower temperature than the vapour. There is a net accumulation of molecules on the surface take place when the arrival rate of vapour molecules is more than the evaporation rate of the vapour molecules from the surface.

Some vapour molecules arrive at the top of first layer before the vapour molecules have completely covered the surface. These vapour molecules arrive at the same rate as before. The rate of evaporation depend on whether the vapour molecules have a greater or lesser affinity for each other than for the cooling surface as the range of atomic force is very small.

The vapour accumulate faster in first layer than second layer than third layer and so on if the surface has an equal or higher affinity for the vapour molecules than the vapour molecules have for each other. Thus the condensing surface covered by layers condensed molecules. It is just like a envelop on condensing surface. In this case the latent heat must be conducted through the layers. Finally these layers slip over each other due to gravity and the condensate flows off without exposing the condensing surface when the number of layers is large. This is filmwise condensation.

On the other hand second, third and subsequent layers are formed only when first layer is completely built and it is possible when the surface has less affinity for the vapour molecules than they have for each other. The condensed vapour molecules combine together into drops, which grow until their weight becomes sufficient to move them over the surface. Here adsorption force between the condensing surface and the first layer is assumed to be smaller than the mutual attraction. When the drop moves downward, these molecules are pulled from condensing surface. This downward movement of drops leaves behind the bare surface where the process can repeat itself. This is known as dropwise condensation.

The space between drops on the condensing surface has an important effect on the phenomena of dropwise condensation. According to Emmons, there must be an envelope of super saturated vapour over the condensing surface between the drops. Condensation occurs very rapidly as these super saturated vapour comes in contact with the surface of drop. Due to which there is a reduction of local pressure which sets up local eddy currents in the vapour between drops. Very high heat transfer coefficient in dropwise condensation is due to this mechanism.

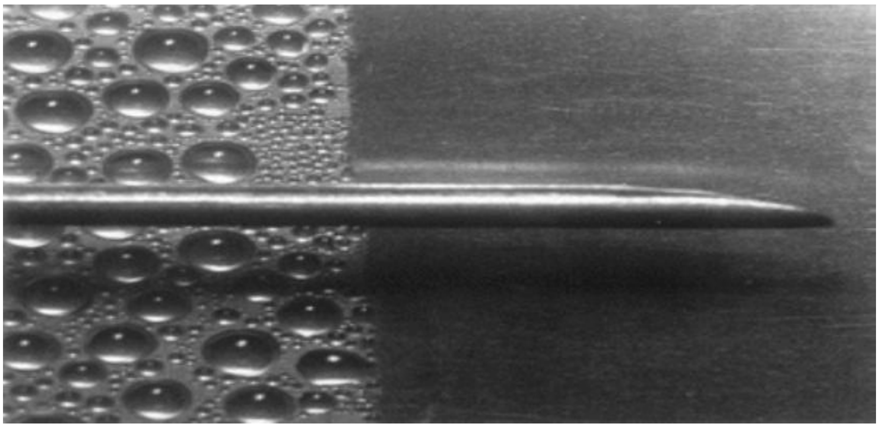


Figure 1: Dropwise & Filmwise Condensation on Vertical Surface [2]

III. EXPERIMENTAL SETUP

Figure 2 show schematic diagram of dropwise condensation apparatus and experimental set up, respectively, which were used for conduct of the experiments.

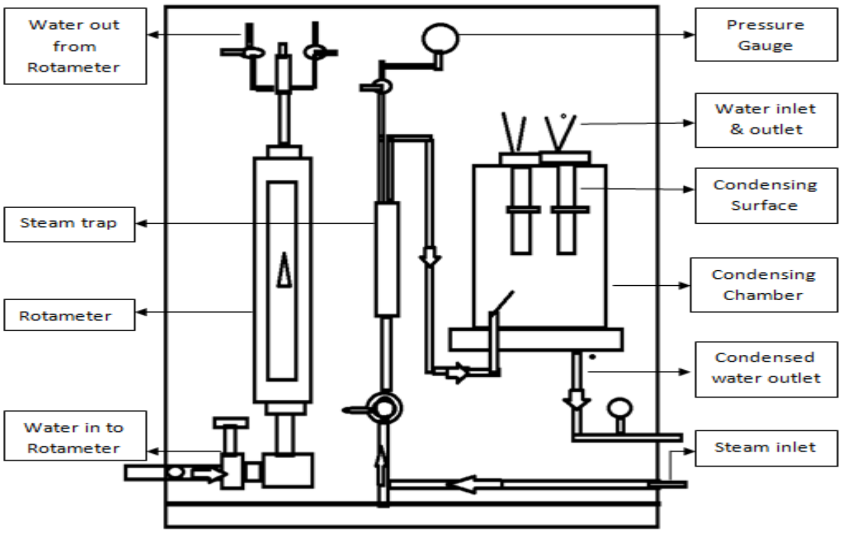


Figure 2: Schematic Diagram of Dropwise Condensation Apparatus

Figure 3: Front View and Back View of Dropwise Condensation Apparatus

Experimental Procedure

Condensing surfaces are placed in the condensing chamber. Two types of condensing surfaces are taken under consideration. Both furnish dropwise condensation due to coating on its outer surface. One is having a chromium coating on copper tube while other is having a silver coating on similar type of copper tube. Steam enters to the steam trap through a pipe from the container where water converts into the steam through electric heater. A valve is placed before the inlet of steam trap to control its flow. Two pipes coming out of steam trap. One is connected to pressure gauge to maintain its required pressure. Other pipe is connected to the condensing chamber. Vapour after getting condensed at the condensing chamber, converted into water and collected at the bottom of condensing chamber. Condensing chamber is made of glass which can sustain higher temperature. As the condensing chamber is made of glass, hence all the processes inside it are clearly visible. Water from a source is pumped to the rotameter (Flow measuring device) at required flow. With the help of valve, required flow rate of water is maintained through the rotameter. Through a separate pipe, water from rotameter passes to the both condensing surface. Thermocouples are placed at various positions to measure the temperature of water and steam. With the help of this measured temperature through digital temperature indicator and flow rate through rotameter, required proposed objectives can be achieved.

IV. OBSERVATION AND CALCULATION PROCEDURE

Table 1: Reading of temperatures at steam pressure = 0.50 kg/cm² & Water flow rate = 60LPH

Thermocouple Positions	Dropwise (chromium coating)	Dropwise (silver coating)
Coated condenser outer surface temp (T_1)	81 °C	81 °C
Steam temp (T_2)	111 °C	112 °C
Water inlet to coated condenser (T_3)	29 °C	29 °C
Water outlet to coated condenser (T_4)	32 °C	33 °C

Table 2: Reading of temperatures at steam pressure = 0.55 kg/cm² & Water flow rate = 60LPH

Thermocouple Positions	Dropwise (chromium coating)	Dropwise (silver coating)
Coated condenser outer surface temp (T_1)	82 °C	83 °C
Steam temp (T_2)	114 °C	114 °C
Water inlet to coated condenser (T_3)	29 °C	30 °C
Water outlet to coated condenser (T_4)	33 °C	34 °C

Table 3: Reading of temperatures at steam pressure = 0.60 kg/cm² & Water flow rate = 60LPH

Thermocouple Positions	Dropwise (chromium coating)	Dropwise (silver coating)
Coated condenser outer surface temp (T_1)	84 °C	86 °C
Steam temp (T_2)	117 °C	117 °C
Water inlet to coated condenser (T_3)	30 °C	30 °C
Water outlet to coated condenser (T_4)	34 °C	35 °C

Table 4: Reading of temperatures at steam pressure = 0.65 kg/cm² & Water flow rate = 60LPH

Thermocouple Positions	Dropwise (chromium coating)	Dropwise (silver coating)
Coated condenser outer surface temp (T_1)	86 °C	89 °C
Steam temp (T_2)	119 °C	120 °C
Water inlet to coated condenser (T_3)	30 °C	30 °C
Water outlet to coated condenser (T_4)	35 °C	36 °C

Governing Equations for Calculation:

- Procedure for calculation of heat transfer coefficient inside the condenser under test are as follows;
- Bulk Mean Temperature; $T_{bulk} = \frac{(T_{wi} + T_{wo})}{2}$ → [12]

  Where T_{wi} = Water inlet temperature to the condenser

  T_{wo} = Water outlet temperature to the condenser
- Take properties density (ρ), kinematic viscosity (ϑ), thermal conductivity (k) & prandtl number of water (Pr) at bulk mean temp (T_{bulk}).
- Reynold's Number; Re = $\frac{4m_w}{\pi D_i \rho \vartheta}$
- Check whether flow is laminar or turbulent. Normally flow will be turbulent in the pipe.
- Nusselt Number; $Nu = 0.0236(Re)^{0.8} \times (Pr)^{0.4}$ → [12]
- Inside heat transfer coefficient; $h_i = \frac{Nu \times k}{L}$
- Procedure for calculation of heat transfer coefficient outside the condenser under test are as follows-
- Bulk Mean Temperature; $T_{bulk} = \frac{T_s + T_{c.\ wall}}{2}$ → [12]

  Where; T_s = Temperature of steam

  $T_{c.\ wall}$ = Outside wall temp of condenser wall
- Take properties density (ρ), thermal conductivity (k), viscosity of condensate (μ) and heat of evaporation of water (h_{fg}) at bulk mean temp (T_{bulk}).
- Outside heat transfer coefficient is given by;

  $$h_o = 0.943 \left[\frac{h_{fg} \times \rho^2 \times g \times k^3}{(T_s - T_{c.\ wall}) \times \mu \times L}\right]^{0.25}$$ → [12]
- Overall heat transfer coefficient; $\frac{1}{U} = \frac{1}{h_i} + \frac{D_i}{D_o} \times \frac{1}{h_o}$ → [12]

  Where;

  D_i = Inside dia. of condenser

  D_o = Outside dia. of condenser

  h_i = Inside heat transfer coefficient

  h_o = Outside heat transfer coefficient

  U = Overall heat transfer coefficient

V. CALCULATIONS

Table 5: Value of parameters at Steam Pressure= 0.50 kg/cm²

Parameters	Chromium Coated Condenser (W/m^2K)	Silver Coated Condenser (W/m^2K)	Percentage Increase
h_i	90.1	92.25	2.38%
h_o	7892.106	8139.918	3.14%
U	89.22	91.356	2.4%

Table 6: Value of parameters at Steam Pressure= 0.55 kg/cm²

Parameters	Chromium Coated Condenser (W/m^2K)	Silver Coated Condenser (W/m^2K)	Percentage Increase
h_i	92.25	94.94	2.92%
h_o	8791.11	9074.18	3.22%
U	91.42	94.089	2.92%

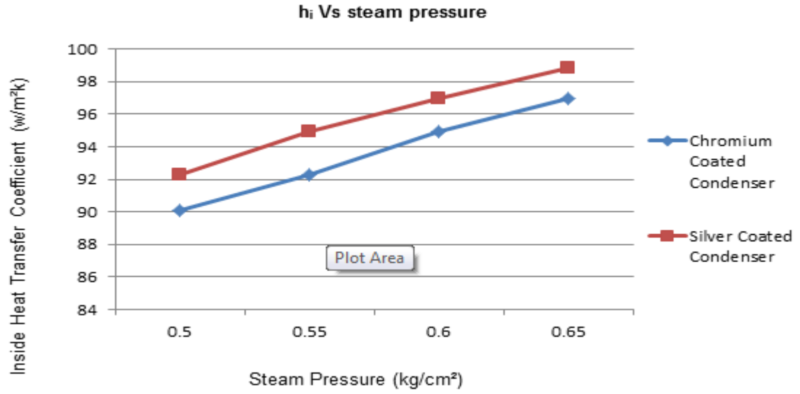
Table 7: Value of parameters at Steam Pressure= 0.60 kg/cm²

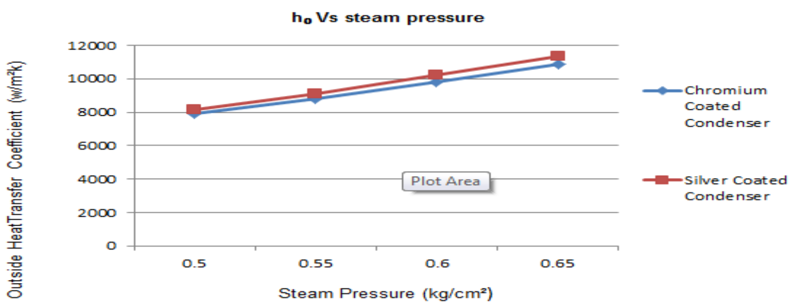
Parameters	Chromium Coated Condenser (W/m^2K)	Silver Coated Condenser (W/m^2K)	Percentage Increase
h_i	94.94	96.97	2.14%
h_o	9825.41	10202.70	3.84%
U	94.154	96.18	2.15%

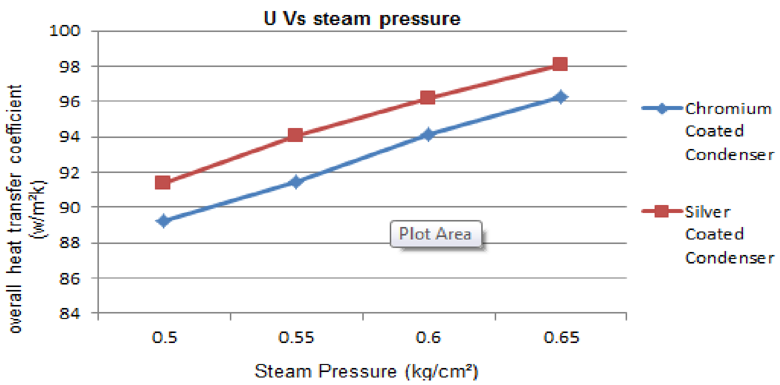
Table 8: Value of parameters at Steam Pressure= 0.65 kg/cm²

Parameters	Chromium Coated Condenser (W/m^2K)	Silver Coated Condenser (W/m^2K)	Percentage Increase
h_i	96.97	98.822	1.91%
h_o	10863.2	11317.27	4.18%
U	96.228	98.082	1.927%

The results obtained above have been plotted as follows:







VI. CONCLUSIONS

(1) It is observed that inside heat transfer coefficient (h_i), outside heat transfer coefficient (h_0) and overall heat transfer coefficient (U) of silver coated condenser of copper is more than that of chromium coated condenser of copper.

(2) The average percentage increase of inside heat transfer coefficient of silver coated condenser to that of chromium coated condenser is 2.3375%.

(3) The average percentage increase of outside heat transfer coefficient of silver coated condenser to that of chromium coated condenser is 3.59575%.

(4) The average percentage increase of overall heat transfer coefficient of silver coated condenser to that of chromium coated condenser is 2.3495%.

(5) The reason behind these results may be due to

- **(a)** Greater affinity of silver with vapour in comparison to chromium.
- **(b)** Lesser wettability of silver coated condenser to that of chromium coated condenser.
- **(c)** Time taken by smaller drops to coalescence into bigger drops is less in silver coated condensing surface. So condensation occurs very rapidly. Due to which there is a reduction of local pressure which sets up local eddy currents in vapour between drops.
- **(d)** Contact angle is inversely proportional to wettability. So silver coated condensing surface is more hydrophobic in nature and having more contact angle than that of chromium coated condensing surface.
- **(e)** Thermal conductivity of silver (k=420W/mK) is more than that of chromium (k=94W/mK).

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