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A Comprehensive Study on the Effects of Surface Roughness on Power Consumption and Heat Transfer Performance in Novel In-Tube Condensation R123yf Refrigerant Systems

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Abstract

This study investigates the impact of surface roughness on the condensation Heat Transfer Coefficient (HTC) of R123yf refrigerant in a uniquely designed test rig with pre-condenser and post-condenser for quality regulation. In mining industries, the mining equipment consumes more amount to power for the Air Conditioning system. To reduce the power consumption of copper metal inside the surface morphology needs to be changed. Experiments were conducted in a 750 mm long, 8.4 mm internal diameter copper tube, with regard to mass flux varying from 150 $kg.m^{-2}.s^{-1}$ to 300 $kg.m^{-2}.s^{-1}$, refrigerant quality varying from 0.3 to 0.8, and saturated temperature from 35°C to 45°C. The impact of varying surface roughness (1.5 µm, 2.5µm, 3.4 µm, and 6.7 µm) on HTC was examined. The plane tube condensation experimental results agreed with M M Shah's heat transfer coefficient correlations, with a 20% absolute mean deviation. It was observed that increasing surface roughness enhanced the HTC. The optimal surface roughness was determined to be 3.4 µm, as it resulted in a significant increase in HTC (26.25%) with a moderate rise in power consumption (15.40%). Higher surface roughness led to a drastic increase in power consumption, making it less desirable for practical applications. Through a systematic analysis of the experimental data, this study identifies the critical trade-off between surface roughness and power consumption, providing guidance for the design of energy-efficient condensation heat transfer systems using R123yf refrigerant. By pinpointing an optimal surface roughness for copper tubes used in refrigeration, this study offers a pragmatic solution for enhancing the efficiency of air conditioning systems in mining equipment, a sector notorious for high energy expenditures. The findings indicate a direct application in mining operations where equipment cooling demands contribute significantly to energy consumption. Implementing the recommended surface modifications can lead to substantial energy savings, thereby reducing operational costs and improving the sustainability of mining activities. Furthermore, the adaptation of R123yf refrigerant systems with optimized surface roughness could serve as a model for energy conservation measures across various facets of the mining industry..

Keywords: *Condensation Heat Transfer, Optimal Surface Roughness, Power Consumption, R123yf Refrigerant, Surface Roughness*

1.0 Introduction

Refrigerants have been thoroughly utilized in various scientific, industrial, and engineering applications, including medicine, food processing, chemical industries, and power plants. They are commonly employed as working fluids in Heating, Ventilation, Air-Conditioning (HVAC), and refrigeration systems. However, many traditional refrigerants have posed environmental challenges due to their high Ozone Depletion Potential

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(ODP) and Global Warming Potential (GWP). As a result, the search for eco-friendly refrigerants has intensified, leading to the development of multiple generations of refrigerants to meet the growing demands while considering environmental impact and maximizing system efficiencies.

The use of volatile fluids as refrigerants dates to 1805 when O. Evans employed them to produce ice by freezing water[1]. Building upon this concept, Perkins developed the first vapor compression refrigeration system in the following years, utilizing ethyl ether as a working fluid[2]. Subsequently, various refrigerants were introduced, including Carbon dioxide (CO_2), Sulphur dioxide (SO_2), Ammonia (NH_3), Hydrocarbons (HCs), and Chlorofluorocarbons (CFCs), which constituted the first generation of refrigerants. These initial refrigerants had limited performance, were highly flammable, and exhibited toxicity concerns. In 1922, propane (R290) replaced ammonia due to its non-toxic nature and improved durability[3]. This marked a shift towards using safer and more reliable refrigerants.

In 1931, CFCs were commercialized after Henne and Midgley discovered that fluorination and chlorination variations influenced the toxicity, boiling point, and flammability of fluorochemical refrigerants[4,5]. Hydrofluorocarbons (HCFCs) emerged as second-generation refrigerants, followed by the identification of their detrimental impact on the ozone layer. In 1997, the stratospheric ozone depletion resulting from refrigerant leakage highlighted the urgent need to phase out Hydrofluorocarbons (HFCs) and Chlorofluorocarbons (CFCs) by 2041[6-7]. Consequently, the Montreal Protocol of 1987 aimed to reduce the usage of chlorinated refrigerants, and the subsequent Kyoto Protocol focused on controlling and minimizing refrigerant emissions to mitigate global warming[8,9]. These protocols prompted the development of low GWP and ODP refrigerants.

The 21st century witnessed the emergence of new refrigerants designed to meet stringent environmental standards. Natural refrigerants, Hydrofluoro Olefins (HFOs), and Hydrochlorofluoro Olefins (HCFOs) are among the alternatives that have been developed and employed[10-13]. One of the extensively used refrigerants in the last three decades has been R134a, an HFC refrigerant, which served as the working fluid in numerous refrigeration systems. Although R134a has zero ODP, its GWP of 1430 contributes to the greenhouse effect[14]. As a result, there has been a shift towards finding suitable alternatives with lower environmental impact. R1234yf, developed by DuPont and Honeywell, exhibits similar thermophysical properties to R134a and possesses zero ODP and a GWP100 (100 years) less than one[15,16]. Additionally, R290, known as propane, has gained attention due to its high performance, non-corrosive nature, and low generation temperatures. However, its high flammability remains a drawback. R290 and R1234yf represent two of the most widely used refrigerants in the 21st century.

The selection of appropriate working fluids for HVAC and refrigeration applications considers various criteria, such as thermophysical properties, environmental considerations (low or zero ODP and GWP), performance (efficiency and capacity), safety (flammability and toxicity), cost-effectiveness, material compatibility, and lubricant miscibility/solubility. R1234yf, widely termed as 2,3,3,3-tetrafluoroprop-1-ene, meets these criteria effectively. It exhibits low toxicity, a lower flammability limit of 6.2 vol% in air, and a minimum ignition energy of 5000-10000 mJ, making it suitable for vehicle air conditioning and refrigeration systems[17-19]. R1234yf is labelled as A2L (low flammability) according to ASHRAE classification, owing to its high ignition temperature of 405°C and low burning velocity at 1.5 cm/s [20]. It is compatible and stable with compressor oils and demonstrates similar behavior to metals, plastics, and elastomers compared to R134a [15]. For its advantageous properties, R1234yf shows tremendous potential as an alternative to HFCs.

Research on R1234yf has increased significantly since 2010, focusing on two-phase flow characteristics, thermodynamic properties, and the design of refrigeration systems utilizing R1234yf [24-30]. Most studies involve experimental and theoretical investigations of flow characteristics and heat transfer during refrigerant condensation in heat exchangers in Vapor Compression Refrigeration (VCR) systems, Ejector Refrigeration (ER) systems, water and air heating/cooling systems, Mobile Air Conditioners (MAC), and residential cooling appliances. Over 800 articles covering more than a decade of research on R1234yf have been reviewed by various researchers[31-34]. However, most of these studies focus on mass fluxes and temperatures below 60 $kg.m^{-2}.s^{-1}$ and

40°C. Moreover, the impact of surface roughness on condensation heat transfer has received limited attention, with only a few studies investigating the effect of surface roughness on condensation for R134a refrigerant.

Ultimately, the evolution of refrigerants has progressed from the first generation, consisting of flammable and toxic substances, to the development of eco-friendly alternatives. The transition from CFCs and HCFCs to Hydrofluorocarbons (HFCs) aimed to reduce ozone depletion and mitigate global warming. However, the high GWP of HFCs necessitated the search for low GWP and ODP refrigerants. R1234yf emerged as a promising alternative with favorable thermophysical properties, low flammability, and environmental friendliness. Extensive research has been conducted on R1234yf, mainly focusing on its flow characteristics and heat transfer in various systems. Nonetheless, even more research is required to analyze the effects of surface roughness on condensation heat transfer, especially for refrigerants like R134a.

The present study aims to study the effects of surface roughness on the condensation heat transfer coefficient of R123yf refrigerant in in-tube condensation systems. The unique design of the experimental setup includes a pre-condenser and a post-condenser, providing quality regulation for accurate measurements. By systematically varying the surface roughness and other parameters, the impact of surface roughness on heat transfer performance and power consumption is evaluated.

To conduct the experiments, a 750 mm long copper tube with an internal diameter of 8.4 mm was used. The mass flux varied between 150 $kg.m^{-2}.s^{-1}$ and 300 $kg.m^{-2}.s^{-1}$, while the refrigerant quality ranged from 0.3 to 0.8. Saturated temperatures ranging from 35°C to 45°C were maintained throughout the experimental investigation. Four different surface roughness levels were considered: 2.5 μm, 2.5 μm, 3.4 μm, and 6.7 μm.

The obtained experimental results are validated with the heat transfer coefficient correlations proposed by M M Shah[36], demonstrating an average absolute mean deviation of 20%. It was observed that an increase in surface roughness positively influenced the HTC. Notably, the optimal surface roughness was identified as 3.4 μm, leading to a significant increase in HTC by 26.25% with a moderate rise in power consumption by 15.40%. However, higher surface roughness resulted in a substantial increase in power consumption, making it less desirable for practical applications.

This comprehensive study offers valuable insights into the critical trade-off between surface roughness, power consumption, and condensation heat transfer performance in in-tube condensation systems utilizing R123yf refrigerant. The findings contribute to the understanding of how varying surface roughness affects the efficiency and energy consumption of such systems. Moreover, the experimental data and analysis provide valuable guidance for the design of energy-efficient condensation heat transfer systems using R123yf refrigerant, considering the optimal surface roughness.

The significance of this research lies in its potential to optimize the design and operation of condensation systems, leading to enhanced energy efficiency, reduced power consumption, and improved environmental sustainability. By understanding the impact of surface roughness on condensation heat transfer performance, engineers and designers can make informed decisions regarding the selection of heat transfer surfaces and the overall system configuration.

The implications of this research extend into mining operations, where HVAC systems play a pivotal role in maintaining safe and comfortable environments for machinery and personnel. In the mining industry, HVAC systems are not only used for climate control but also for ventilation and air quality management, crucial for health and safety due to underground mining emissions. Enhanced condensation heat transfer performance, as investigated in this study, could significantly reduce the energy consumption of such systems. This is particularly pertinent to the mining sector, which is energy-intensive and is often located in remote areas where energy efficiency is paramount. Implementing improved heat transfer techniques in the air conditioning systems of mining operations can lead to reduced power requirements, thereby lowering the energy footprint and operational costs. Adapting energy-efficient refrigerants like R123yf with optimised surface roughness for condensation could, therefore, represent a substantial stride towards greener and more cost-effective mining processes.

Moreover, the heat exchange efficiency in critical mining equipment directly affects the longevity and reliability of the machinery used in excavation, processing, and transportation. By advancing our understanding of the condensation heat transfer characteristics of newer, environmentally friendly refrigerants and optimising surface roughness, this study offers a path to enhance the performance of mining equipment cooling systems. This is especially beneficial in mitigating the extreme thermal loads encountered by such equipment, ultimately improving operational efficiency and reducing downtime. In conclusion, the adoption of the findings from this research could help in achieving more sustainable and economically viable mining operations, thereby contributing to the broader goals of energy conservation and environmental protection within the industry.

2.0 Experimental Test Rig and Procedure

Figure 1 illustrates the schematic representation of the novel test rig employed in this study. The test rig comprises several components, including a pre-condenser, condenser test section, post-condenser filter dryer, thermostatic expansion valve (TXV), evaporator, and compressor. The refrigerants enter the compressor in either a saturated or superheated steam state from the evaporator. Before entering the condenser test section, the refrigerant quality is regulated in the pre-condenser. In the condensers, the refrigerant undergoes the process of condensation, resulting in its transformation to a state close to liquid. Cold water is supplied to the condenser from a chiller installed in the post-condenser section. The condensed refrigerant passes through a filter dryer area where it is filtered and dehumidified before entering the expansion valve. The subcooled refrigerant is then

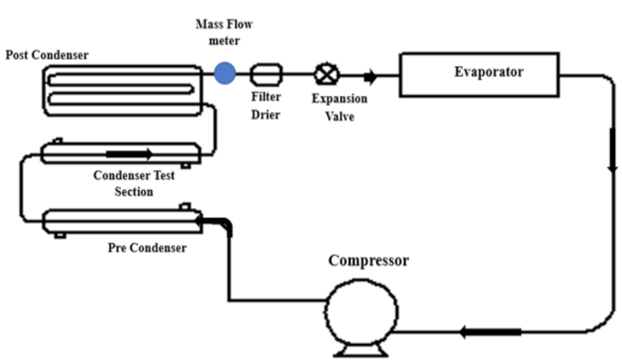

Figure 1. Test rig schematic.

throttled isentropically through the expansion valve to form a liquid-vapor mixture. The cycle then continues in the evaporator with this liquid-vapor mixture at low pressure and temperature.

In the test rig copper tubes with a 8.4 mm internal diameter and a 9.1 mm exterior diameter are used for the experimental setup. To monitor the pressures and refrigerant mass flow rates, a differential pressure gauge was installed between the post-condenser and filter dryer in the test rig. Additionally, nine k-type thermocouples and three differential pressure gauges were strategically placed at various locations within the test rig to measure temperature variations.

Before commencing the experimentation, a leakage test was conducted to ensure the absence of any leaks in the test rig, particularly under vacuum pressures ranging from 0 bar to 10 bar. Subsequently, the R1234yf refrigerant was charged into the system at a pressure of 1500 mmHg. The condensation of R1234yf vapor in the test section occurs because of heat transfer to the counterflowing water. Further cooling of the refrigerant takes place in the post-condenser, where it is transformed into a sub-cooled liquid state due to heat transfer to the circulated cold water. Finally, the heated refrigerant flows into the evaporator before entering the compressor, thus completing the cycle.

The experimental investigations were conducted under various saturation temperatures and pressures by manipulating the coolant mass flow rates and compressor speeds. To examine the influence of surface roughness on the HTC, copper tubes with three distinct surface roughness values (2.5 µm, 3.4 µm, and 6.7 µm) were employed in the test sections. The surface roughness of the copper tube samples used in the experiments was evaluated through the analysis of optical microscopic images and surface roughness profile images. The

Table 1. Test Conditions

Pressure	0 to 10 bar
Refrigerant quality	0.3 - 0.8
Mass flux	150 -300 kg.s^{-1}/m^2
Surface roughness	2.5 µm, 3.4 µm, and 6.7 µm

mean surface roughness (Ra) was determined using a profilometer, while industrial microscopes were utilized to visualize the surface roughness of the copper samples.

The experimental operating conditions, including the variability of refrigerant mass flow rate from the pre-condenser and the different copper tube surface roughness values, are summarized in Table 1. To record the refrigerant properties, digital data loggers were employed. Subsequently, the recorded data was processed and analyzed using REFPROP software and MATLAB to calculate the HTC of the R123yf refrigerant in the test section.

3.0 Data Reduction

The refrigerant's mass flow rate was determined using the Haaland equation[28], which is expressed as follows:

$$\Delta P=(l_p*\rho_l*(V_l)^2)/(2*d_i) \quad (1)$$

$$1/f=-1.8\log[(e/(3.7*d_i))^{1.11}+6.9/R_{el}] \quad (2)$$

$$R_e=(\rho_l*V_l*d_l)/\mu_l \quad (3)$$

$$m_r=\rho_l*A_p*V_l \quad (4)$$

The heat transfer rate in the pre-condenser determines the quality of the refrigerant vapour at the pre-condenser section intake.

$$(Q_w)_{PC}=m_w*c_{pw}(T_{w2}-T_{w1})_{PC} \quad (5)$$

The heat that water carries is equivalent to the heat that the refrigerant loses in the pre-condenser stage.

$$(Q_w)_{PC}=(Q_r)_{PC} \quad (6)$$

The refrigerant's enthalpy at the pre-condenser outlet is

$$(h_{r2})_{PC}=(h_{r1})_{PC}-(Q_r)_{PC}/m_r \quad (7)$$

The refrigerant's vapour quality is calculated as

$$X_1=((h_{r1})_{PC}-h_f)/h_{fg} \quad (8)$$

In a similar manner, the refrigerant X2 quality at the test section's exit is determined as follows:

$$X_{avg}=(X_1+X_2)/2 \quad (9)$$

4.0 Results and Discussions

The relationship between power consumption, surface roughness, and mass flux was examined based on the findings presented in Figure 2. It is evident that power consumption increases with an elevation in both surface roughness and mass flux. Specifically, for copper tubes with a surface roughness of 2.5 µm, the average power consumption exhibited a noticeable rise of 9.71% across mass flow rates ranging from 150 kg.s^{-1}m^{-2} to 300 kg.s^{-1}m^{-2}. Consequently, this increase in power consumption led to a substantial enhancement of 20.51% in HTC when compared to the plain tube.

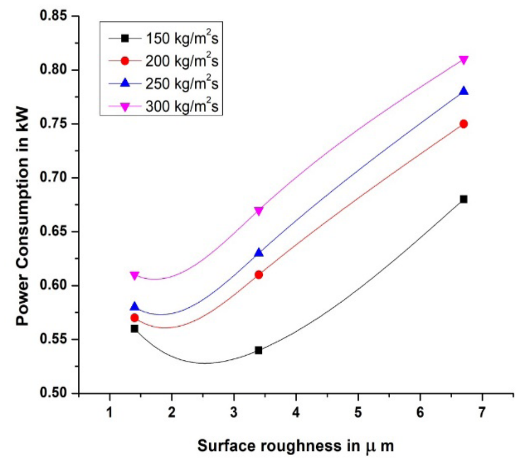

Figure 2. Power consumption vs surface roughness.

Furthermore, for copper tubes featuring a surface roughness of 3.4 µm, the average power consumption displayed a more pronounced increase of 15.40% across the same mass flow rate range. As a result, the HTC experienced a considerable rise of 26.51% compared to the plain tube. It is worth noting that the rise in power consumption was more significant for this surface roughness value, indicating a stronger impact on energy consumption.

In contrast, the copper tube with a surface roughness of 6.7 µm exhibited a drastic average power consumption increase of 42.40% within the considered mass flow rate range. Consequently, the HTC showed a notable increase of 31.72% when compared to the plain tube. These results highlight the significant effect of higher surface roughness on power consumption, which may limit its practical application due to the substantial rise in energy requirements.

5.0 Conclusions

The results obtained from this study provide valuable insights into the impact of different internal surface roughness values on power consumption and Heat Transfer Coefficient (HTC) in copper tubes. Firstly, it was observed that for copper tubes with an internal surface roughness of 2.5 μm, the average power consumption exhibited a gradual increase of 9.71% compared to the plain tube. Consequently, this increase in power consumption corresponded to a notable enhancement of 20.52% in the HTC when compared to the plain tube. These findings suggest that a moderate surface roughness value of 2.5 μm can yield improved heat transfer performance without a substantial increase in power consumption.

Moving on to copper tubes with an internal surface roughness of 3.4 μm, the average power consumption displayed a more significant increase of 15.40% compared to the plain tube. This rise in power consumption was accompanied by a considerable increase in HTC, amounting to 26.25% when compared to the plain tube. It is worth noting that the increase in power consumption was more pronounced for this surface roughness value, indicating a stronger impact on energy consumption. Nevertheless, the notable improvement in the HTC suggests that the use of copper tubes with an internal surface roughness of 3.4 μm could be beneficial in applications where enhanced heat transfer is prioritized, even if it results in higher power consumption.

In contrast, the results showed a drastic average power consumption increase of 42.40% compared to the plain tube for copper tubes with an internal surface roughness of 6.7 μm. This substantial rise in power consumption corresponded to a significant increase in HTC, amounting to 31.73% when compared to the plain tube. The findings indicate that the power consumption experienced a sharp escalation beyond the 3.4 μm internal surface roughness value. Consequently, caution must be exercised when considering copper tubes with higher surface roughness values, as they lead to a considerable increase in energy requirements.

Ultimately, the experimental results highlight the trade-off between internal surface roughness, power consumption, and heat transfer performance in copper tubes. The findings demonstrate that the internal surface roughness value of 3.4 μm strikes a favorable balance, resulting in a notable increase in HTC with a manageable rise in power consumption. This suggests that utilizing copper tubes with this specific surface roughness value can offer improved heat transfer characteristics while minimizing the associated energy consumption. The copper tubes with such surface roughness used in Air conditioning condenser of Mining equipment appreciable amount of power can be saved.

The findings of this study bear significant ramifications for the mining industry, where HVAC systems are critical to maintaining operational efficiency and safety standards. By adopting copper tubes with an optimal internal surface roughness of 3.4 μm within mining equipment air conditioning systems, operations can achieve enhanced heat transfer efficiency, leading to reduced thermal stress on critical components and lower energy consumption. This optimization has the potential to translate into longer equipment life spans, reduced maintenance costs, and improved overall sustainability of mining operations. Moreover, the energy savings achieved through such optimizations are in alignment with the industry's ongoing efforts to minimize environmental impact and operational expenses, reinforcing the study's relevance to the modern mining sector's push towards greener and more cost-efficient practices.

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Appendix

A_{ti} : pipe's internal surface area (m2)
c_{pw} : Water's specific heat (J/kg K)
K_l : Thermal Conductivity of liquid refrigerant (W/m K)
h : Enthalpy (kJ/kg)
HTC : Heat Transfer Coefficient
G : Refrigerant's mass flux of (kg/m2s)
m_r : Mass flow rate (kg/s)
P : Pressure
P_r : Prandtl number
p_r : reduced pressure
Q : Heat transfer rate (W)
T : Temperature (°C)
X : Dryness fraction
Z : MM Sha's Correlating factor

Greek Symbols

α : Refrigerant's HTC (W/m2 K)
λ : Thermal conductivity (W/m.K)

Subscripts

avg : average
exp : experimental
i : inside, refrigerant side
g : gaseous /vapor
f : the friction factor of the pipe
l : liquid
lo : liquid only
MMS: MM Shah's
nu : Nusselt number
p : pipe
PC : pre-Condenser
o : outside
r : refrigerant
s : saturated
w : water
sat : saturation
TC : condenser Test Section
1 : inlet
2 : exit