Investigation of Coatings to Enhance Heat Transfer Efficiency

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Abstract—*The performance of heat exchangers plays a vital role in energy industries, where even marginal improvements in heat transfer efficiency can lead to significant cost savings and performance gains. In this study, we explore an innovative approach to enhancing heat exchanger efficiency by applying surface coatings. Unlike geometric modifications, coatings offer the advantage of improving thermal performance without altering the exchanger's design. This project involves an experimental investigation into the effects of various thermal coatings on heat transfer rates. We aim to identify coatings that optimize thermal conductivity and heat exchange efficiency by comparing coated and uncoated surfaces under controlled conditions. The findings can contribute to developing more efficient and sustainable thermal systems in industrial applications.*

Keywords—*heat exchanger efficiency, thermal coatings, experimental investigation*

1. Introduction

The heat exchanger is a critical component used to transfer heat between two or more fluids. These devices are widely employed across various industries, including power generation, chemical processing, refrigeration, automotive, and HVAC systems. The overall efficiency of a heat exchanger significantly impacts operational costs, energy consumption, and system performance.

Improving heat exchanger efficiency is therefore of considerable interest. Traditional approaches often involve increasing the surface area for heat exchange or optimizing flow arrangements. However, these changes may lead to higher manufacturing costs or design complexity. An emerging alternative is specialized surface coatings that can enhance thermal performance without altering the exchanger's geometry.

Surface coatings can improve thermal conductivity, modify surface wettability, or reduce fouling, contributing to enhanced heat transfer. In this project, we experimentally investigate the impact of different surface coatings on the heat transfer efficiency of heat exchangers. The goal of analyzing thermal performance across various coated surfaces is to identify which materials and coating types yield the most improvement under identical operating conditions.

This research aims to provide practical insights into the effectiveness of coatings and explore the sustainable and cost-effective heat exchanger enhancements in industrial applications.

2. Experimental Setup

The experimental setup is designed to evaluate the effect of surface coatings on the heat transfer performance of a coiled copper tube submerged in hot water. Each component is selected to facilitate controlled testing under consistent conditions.

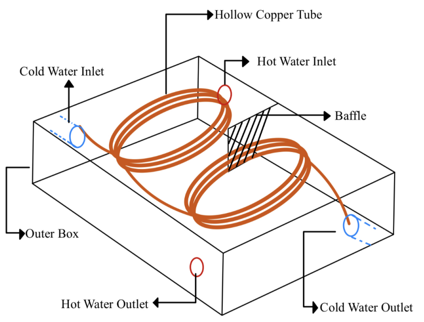

Figure 1. Initial Setup

- **Heat Exchanger Pipe:** A coiled copper pipe serves as the main element for heat exchange due to its high thermal conductivity and flexibility. The coil allows for easy removal and reinstallation during coating tests.
- **Containment Box:** The hot water is pumped in a box made of Acrylonitrile Butadiene Styrene (ABS), which can safely operate within a temperature range of $-20°C$ to $80°C$. Our experimental conditions lie between $10°C$ to $60°C$, making ABS a suitable and cost-effective choice.
- **Water Circulation System:** Two pumps are incorporated—one to circulate hot water into the ABS box and the other to drive cold water through the copper coil. This arrangement ensures continuous heat exchange under steady flow conditions. A counter-flow arrangement is maintained to enhance the heat transfer.
- **Piping:** Transparent tubing is used for hot water inflow. Blue tubing is used for the cold water circuit, connected directly to the copper coil.
- **Thermal Control and Measurement:** Thermocouples are used to measure the inlet and outlet temperatures of the hot and cold fluid flow.
- **Sealing Agents:** Mseal and tape are used to ensure a leakproof design.
- **Insulation Tape:** It is use to insulate the hot and cold reservoirs.
- **Modular Design:** The setup allows simple detachment of the copper tube, enabling efficient coating and reinstallation without disturbing the overall system configuration.

3. Experimental Procedure

3.1. Surface Preparation

The surface of the heat exchanger plates was prepared using three different types of coatings. Each coating was applied following a specific procedure to ensure consistency and uniformity.

3.1.1. Acrylic Paint Coating

1. The surface was cleaned using sandpaper to remove any dust, grease, or existing layers.
2. A single layer of dark colored acrylic paint was applied uniformly using a brush.
3. The coated plate was allowed to dry at room temperature.
4. Same procedure was repeated for a light colored acrylic paint.

3.1.2. Hydrophobic Coating

1. The copper surface was first cleaned using acetone and then placed in an oven at $80°C$ for five minutes to eliminate any residual moisture.
2. A mixture of 0.1 mL Perfluorodecyltrimethoxysilane and 0.9 mL toluene was prepared in a small beaker. This beaker and the cleaned copper pipe were placed inside a glass container.
3. The container was covered with aluminium foil and heated in an oven at $80°C$ for five hours to facilitate vapor deposition.
4. During heating, the silane-toluene mixture vaporized and condensed onto the copper surface, forming a hydrophobic coating.
5. To ensure uniform deposition, the pipe was rotated halfway and the procedure was repeated, allowing the opposite side to be coated.

3.1.3. Nanomaterial Coating: Titanium Diboride TiB_2

1. The surface was first cleaned with acetone and then placed in an oven at $120°C$ for five minutes to remove any residual moisture.

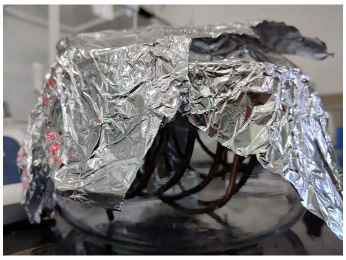

Figure 2. Hydrophobic Coating Setup

2. The copper pipe was immersed in a 1500 mL solution containing 98% ethanol and 2% silane solution (3-Triethoxysilylpropylamine by volume) for 20 minutes to promote surface functionalization.
3. After rinsing, the pipe was transferred into a suspension of TiB_2 nanosheets and left to soak for another 20 minutes to allow the nanomaterial to adhere to the surface.
4. Finally, nitrogen (N_2) gas was used to gently dry the coated surface, which was then left undisturbed at room temperature for 5 hours to complete the process.
5. The silane solution is negatively charged, and the TiB_2 suspension is positively charged. The electrostatic attraction deposits a nanomaterial coating on the surface.

Figure 3. Nanomaterial Coating Setup

3.2. Experimental Procedure

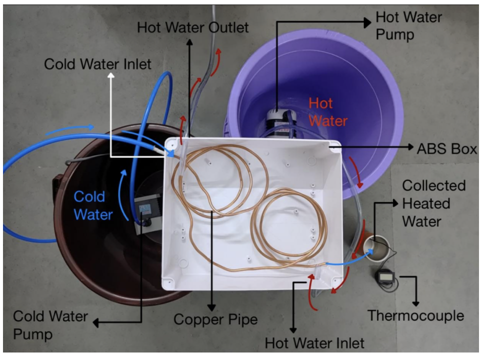

Figure 4. Final Experimental Setup

After the coated or uncoated copper pipe was prepared, it was fitted into the experimental setup to measure heat transfer performance. The following steps were followed for each test case:

- The coated or uncoated copper coil was securely placed inside the ABS box.
- The inlet temperatures of the hot and cold water in the reservoirs were measured before starting the system.
- Hot water was pumped into the box using a submersible pump until the copper coil was fully submerged.
- Simultaneously, another pump pumped cold water through the copper pipe.
- The cold water entered the copper pipe from one end and exited from the other, absorbing heat from the surrounding hot water.
- Thermocouples were placed at the outlets, and the hot and cold water outlet temperatures were recorded. Multiple readings were taken, and the mean value was used.
- This process was repeated for each coating (acrylic, hydrophobic, nanomaterial).
- After each trial, the copper pipe was removed, cleaned if required, and replaced with the following prepared sample.

4. Baseline Calculation

Assumptions

- The readings taken are at steady state
- Constant wall temperature of copper pipe.
- The fouling factor in calculating overall resistances is neglected.

Consider the initial experiment performed with an uncoated copper pipe. The net heat transfer coefficient U_o (outer) can be calculated using the following relations -

$$R_{net} = \frac{1}{U_o \cdot A_o}$$

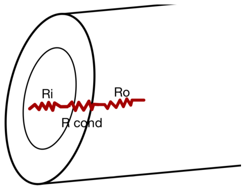

Figure 5. Thermal Resistance in Series

The net resistance involves a series combination of three resistances - Inner Convection, Conduction Outer Convection.

$$R_{net} = R_i + R_{wall} + R_o$$

$$R_{net} = \frac{1}{h_i \cdot A_i} + \frac{\ln \frac{R_o}{R_i}}{2 \cdot \pi \cdot k \cdot l} + \frac{1}{h_0 \cdot A_o}$$

The recorded readings of the Thermocouples are - The Properties

Fluid	Inlet (°C)	Outlet (°C)	Average (°C)
Hot Water	54	47	50.5
Cold Water	18	42	30.0

Table 1. Baseline Results for Uncoated Copper Tube

of Fluids, Hot and Cold Water at their respective average temperature, are considered for the calculation of the net coefficient of heat transfer, which are tabulated below -

Property	At 50.5°C	At 30°C
Density (kg/m^3)	988.1	995.87
Viscosity (mPa·s)	0.547	0.797
Specific Heat Capacity (J/kg·K)	4182	4178
Thermal Conductivity (W/m·K)	0.643	0.613

Table 2. Thermophysical Properties of Water at Measured Temperatures

The dimensions of the heat exchanger are -

Inner Diameter: $D_i = 0.003\,\text{m}$
Outer Diameter: $D_o = 0.005\,\text{m}$
Length of pipe: $l = 3\,\text{m}$

Pump Specifications -

$$\text{Flow rate } \dot{Q} = 1100L/hr$$

4.1. R_i Calculation

The velocity of the fluid is given by:

$$v = \frac{\dot{Q}}{A} = \frac{\dot{Q}}{\frac{\pi}{4}D^2}$$

Substituting the values:

$$v = 43.22m/s$$

The Reynolds' Number and Prandtl Number are calculated using the below realtions and used to calculate the Nusselt number using the realtion for external flow around a cylinder -

$$\mathrm{Re}_D = \frac{\rho v D}{\mu}; P_r = \frac{C_p \cdot \mu}{k}$$
$$Nu = 0.023 \cdot Re_D^{0.8} \cdot P_r^{0.4}$$
$$Nu = 665.813$$

Using the relation between the Nusselt number and Coefficient of convection

$$h_i = 1.3605 \times 10^5 W/m^2K$$

Therefore, the inner resistance can be calculated as -

$$R_i = 2.6 \times 10^{-4} K/W$$

4.2. $R_{conduction}$ Calculation

$$R_{cond} = \frac{\ln \frac{R_o}{R_i}}{2 \cdot \pi \cdot k \cdot l}$$
$$R_{cond} = 6.76 \times 10^{-5} K/W$$

4.3. R_o Calculation

Similar to the calculation of the inner convection coefficient calculation Re_l and P_r are calculated and substituted in the Nusselt number equation for internal flow in a cylindrical pipe.

$$\mathrm{Nu} = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1 + \left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}} \left(1 + \left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right)^{4/5}$$
$$Nu = 5445$$

Using the relation between the Nusselt number and Coefficient of convection

$$h_o = 1.1692 \times 10^3 W/m^2K$$

Therefore, the outer resistance can be calculated as -

$$R_i = 0.01815 K/W$$

Using the above relation for net resistance, we can calculate U_o as -

$$R_{net} = \frac{1}{U_o \cdot A_o}$$
$$U_o = 1148.46 W/m^2K$$

5. Results

The results of the heat transfer experiments for the three different tube conditions — Uncoated, Acrylic Coated, and Hydrophobic Coated — are presented below. The calculations are performed using a Python script. The QR Code to the Colab Link is attached below -

5.1. Uncoated Copper Tube

Parameter	1	2	3
Hot Inlet (°C)	54.0	49.0	60.8
Hot Outlet (°C)	47.0	43.3	53.6
Cold Inlet (°C)	18.0	16.8	16.3
Cold Outlet (°C)	42.0	41.1	49.0
U_o (W/m^{2}K)	1148.46	1092.60	1243.01

The average overall heat transfer coefficient for the uncoated tube is calculated as:

$$U_o = \bar{U}_o \pm \Delta U_o = 1161.35 \pm 76.03 \text{ W/m}^2\text{K}$$

5.2. Acrylic Coated Tube (Light)

Parameter	1	2	3	4
Hot Inlet (°C)	50.9	52.7	55.9	53.5
Hot Outlet (°C)	46.8	47.7	51.1	48.8
Cold Inlet (°C)	12.5	14.4	14.8	14.9
Cold Outlet (°C)	35.4	40.8	43.1	39.3
U_o (W/m^{2}K)	1112.16	1148.15	1193.40	1172.89

The average overall heat transfer coefficient for the light acrylic-coated tube is calculated as:

$$U_o = \bar{U}_o \pm \Delta U_o = 1156.65 \pm 34.96 \text{ W/m}^2\text{K}$$

5.3. Acrylic Coated Tube (Dark)

Parameter	1	2	3
Hot Inlet (°C)	52.0	58.0	50.8
Hot Outlet (°C)	46.0	50.0	45.0
Cold Inlet (°C)	13.8	13.0	14.5
Cold Outlet (°C)	40.1	44.0	48.6
U_o (W/m^{2}K)	1112.53	1193.40	1113.42

The average overall heat transfer coefficient for the dark acrylic coated tube is calculated as:

$$U_o = \bar{U}_o \pm \Delta U_o = 1139.78 \pm 46.43 \text{ W/m}^2\text{K}$$

5.4. Hydrophobic Coated Tube

Parameter	1	2	3	4
Hot Inlet (°C)	52.4	57.1	54.9	53.7
Hot Outlet (°C)	48.1	49.7	49.3	49.4
Cold Inlet (°C)	12.1	13.3	14.6	15.6
Cold Outlet (°C)	37.3	42.1	39.8	38.8
U_o (W/m^{2}K)	1147.43	1193.40	1172.89	1172.89

The average overall heat transfer coefficient for the hydrophobic-coated tube is calculated as:

$$U_o = \bar{U}_o \pm \Delta U_o = 1172.65 \pm 37.02 \text{ W/m}^2\text{K}$$

The acrylic coating was applied in a manner that allowed it to be easily removed without damaging the copper surface. As a result, the same copper tube was reused for the hydrophobic coating experiment.

However, the hydrophobic coating, once applied, formed a permanent layer that could not be removed without compromising the integrity of the tube. Consequently, another copper tube of different dimensions is used for the nanomaterial coating.

$$\text{Inner Diameter: } D_i = 0.005\,\text{m}$$
$$\text{Outer Diameter: } D_o = 0.006\,\text{m}$$
$$\text{Length of pipe: } l = 4\,\text{m}$$

To ensure consistency in comparison, both the hydrophobic-coated and nanomaterial-coated tubes were analyzed separately and benchmarked against their respective baseline results of the uncoated tube. This approach enabled a comparative evaluation of the thermal performance enhancement provided by the nanomaterial coating relative to the uncoated configuration.

5.5. Second Uncoated Tube

Parameter	1	2	3	4
Hot Inlet (°C)	48.7	48.8	48.5	48.0
Hot Outlet (°C)	44.0	44.8	44.2	37.8
Cold Inlet (°C)	18.5	19.2	18.0	17.6
Cold Outlet (°C)	38.3	46.2	46.2	33.9
U_o (W/m^{2}K)	1059.67	1060.62	1060.62	1025.43

The average overall heat transfer coefficient for the second uncoated tube is calculated as:

$$U_o = \bar{U}_o \pm \Delta U_o = 1051.59 \pm 17.45\ \text{W/m}^2\text{K}$$

5.6. Nanomaterial Coated Tube

Parameter	1	2	3
Hot Inlet (°C)	56.9	50.1	60.5
Hot Outlet (°C)	49.9	46.3	53.5
Cold Inlet (°C)	11.2	12.8	15.2
Cold Outlet (°C)	44.1	40.8	46.0
U_o (W/m^{2}K)	1158.32	1078.96	1181.91

The average overall heat transfer coefficient for the nanomaterial-coated tube is calculated as:

$$U_o = \bar{U}_o \pm \Delta U_o = 1139.73 \pm 53.94\ \text{W/m}^2\text{K}$$

The above results can be summarized as follows -

Coating Type	$\bar{U}_o$ (W/m^{2}K)
Uncoated Tube (Original)	1161.35
Acrylic Coated Tube (Light)	1156.65
Acrylic Coated Tube (Dark)	1139.79
Hydrophobic Coated Tube	1172.65
Second Uncoated Tube	1051.59
Nanomaterial Coated Tube	1139.73

Table 3. Summary of Average Overall Heat Transfer Coefficients

6. Discussions

6.1. Comparison of Coatings and Uncoated Pipe

From the data, it is evident that the hydrophobic coating results in the highest heat transfer coefficient, with an average value of 1172.65 W/m^{2}K. This suggests that the hydrophobic coating is the most effective in enhancing heat transfer efficiency among the coatings tested. The increase in the heat transfer coefficient compared to the uncoated tube (1161.35 W/m^{2}K) could be attributed to the reduced resistance to heat flow, which is a typical characteristic of hydrophobic coatings that improve surface wettability and promote better heat exchange in such systems.

On the other hand, the acrylic-coated tubes (both light and dark) show marginally lower heat transfer coefficients than the uncoated tube. Specifically, the light acrylic coating results in 1156.65 W/m^{2}K, and the dark acrylic coating performs slightly worse at 1139.79 W/m^{2}K. The color of the acrylic coating can influence heat transfer due to its effect on emissivity and thermal resistance. Darker surfaces, such as the dark acrylic coating, typically have higher emissivity, meaning they radiate heat more effectively. However, this can reduce the overall heat transfer efficiency if the system relies on conductive or convective heat transfer, as heat is lost through radiation rather than being transferred to the fluid. In contrast, lighter coatings reflect more heat and have lower emissivity

6.2. Comparison of Nanomaterial and Uncoated Pipe

When comparing the second uncoated tube to the nanomaterial-coated tube, we observe that the nanomaterial coating leads to a heat transfer coefficient of (1139.73 W/m^{2}K) which is higher than the second uncoater copper tube, (1051.59 W/m^{2}K). This improvement can be attributed to the superior thermal conductivity of the nanomaterials like TiB_2, which facilitate more efficient heat transfer across the surface. Nanomaterials often have extremely high surface area-to-volume ratios and excellent thermal properties at the nanoscale, which enhance conduction at the solid-fluid interface.

7. Sources of Errors

Several factors could contribute to the observed discrepancies in heat transfer performance, including:

- Variations in the thickness of the coatings could result in uneven heat transfer performance.
- If the surface preparation for coating application was not consistent across all tests, this could have led to differences in the effectiveness of each coating.
- Potential errors in temperature readings measurements could affect the accuracy of the results.

8. Conclusion

This study aimed to investigate the effect of various surface coatings on the heat transfer efficiency of copper tubes in a heat exchanger setup. Through systematic experimentation and analysis, it was observed that surface modification can enhance or degrade the performance based on surface properties. While hydrophobic coatings marginally improved heat transfer, acrylic coatings—especially darker variants—tended to reduce efficiency. Most notably, nanomaterial coatings demonstrated a marked enhancement in heat transfer compared to their uncoated counterpart. Overall, the findings underscore the importance of surface engineering in optimizing heat exchanger performance.

References

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[2] S.P. Sukhatme and J.K. Nayak, *A Textbook on Heat Transfer*, 4th ed., Universities Press, 2008.

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