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Novel Visualization Method to Quantify Local Air-side Heat Transfer Coefficient

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ABSTRACT

Low air-side heat transfer coefficients (HTC) are often the bottleneck of heat exchanger performance. However, the measurement of local air-side heat transfer coefficients for the entire heat transfer surface is not a trivial task. Current experimental methods often only work on scaled-up samples which typically cannot deliver continuous HTC distributions across the surface of interest. Moreover, some methods require very precise and costly equipment such as lasers. Therefore, a novel visualization method is designed to obtain local air-side HTC distributions of an entire heat exchanger with a relatively simple experimental facility. The method relies on measuring mass transfer and applying the analogy between heat and mass transfer to determine heat transfer. The process involves a thin acidic coating on the heat transfer surface which is exposed in a wind tunnel to a suitable trace gas, in this case a low concentration ammonia-air mixture. The coating will absorb the ammonia and gradually change color from yellow to green to blue, depending on the exposure time and local ammonia concentration. By observing the color difference, the mass transfer could be acquired and local HTC is calculated subsequently. In order to develop this method, different metal samples such as aluminum, copper and stainless steel were coated and tested. The thickness and evenness of coatings are measured by a stylus profiler. The results show that the coating characteristic will not have a significant impact on airflow and the boundary layer conditions. So, the conditions of applying the analogy between mass and heat transfer are fulfilled. Preliminary mass transfer experiments show continuous color change on a flat plate which is proportional to mass transfer of ammonia from the free stream flow to the coated surface. Thus, this new method is very promising to acquire local HTC with a visualization approach on different geometries.

1. INTRODUCTION

1.1 Motivation for Developing a Novel Visualization Method

Liquid-to-air, two-phase-to-air and air-to-air heat exchangers are widely used in many areas such as refrigeration, air-conditioning, power generation, industrial processes among others. Enhanced heat exchanger performance could increase the efficiency of the entire system, allowing for reduced heat exchanger sizes. This could lead to more compact products, and materials and energy cost could be reduced. Therefore, by improving heat exchanger designs, the system could be smaller, lighter, and cheaper and save operating energy cost. The research of heat exchanger is mainly focusing on two aspects. Liquid or two-phase side enhancements and air-side enhancements. By now air-side resistance has been found to be the largest contributor to heat transfer resistance and is generally seen as the bottleneck of heat exchanger performance. Pioneer researchers investigated heat transfer coefficient (HTC) and pressure drop as key factors to evaluate heat exchangers. However, it is extremely difficult to acquire local heat transfer coefficients either experimentally or mathematically on complicated geometries. There are several existing methods to investigate HTC such as Wilson plot, thermochromic liquid crystal (TLC), infrared thermography (IRT), particle image

velocimetry (PIV) and naphthalene sublimation. However, many of those methods listed have limitations to quantify local HTC.

The novel visualization method is based on the analogy of convective mass and heat transfer. There are three steps of applying this novel method. Firstly, a thin film coating will be applied to form a uniform coating across the entire solid surface. The sample will then be located in the wind tunnel in which a tracer gas is mixed with the air flow. During this process, the coating will absorb the tracer gas and respond with a visible color change. As the intensity of the color represents the quantity of the mass transfer, color change, mass transfer, and heat transfer could be correlated. There are several potential advantages of this novel method. Firstly, the coating is easy to apply on complicated surfaces of actual heat exchangers. Therefore, it is possible to measure local HTC of complicated and entire heat exchanger surfaces. Secondly, the color change can be controlled as to when and where it occurs, because tracer gas is required to initiate the process through reaction with the coating material and cause a color change. Once the tracer gas is isolated from the coated surface, the color change will stop. Thirdly, there is no expensive materials, complicated procedures, or costly equipment required. A conventional digital camera and a simple wind tunnel are available in many laboratories.

1.2 Brief Review of Existing HTC Experimental Methods

1.2.1 Wilson Plot Method

The so-called Wilson plot method was first proposed by Wilson (1915). It relies on the basic principle that the overall thermal resistance is the sum of the thermal resistances of each layer or process involved. Fernández-Seara *et al.* (2007) generated a review of the Wilson plot method and its modifications which shows that this method is easy to apply. It is therefore widely used in both academic and industrial laboratories for the analysis and design of convection heat transfer system. This method avoids direct measurement of surface temperature. Empirical equations for various heat transfer applications have been generated by previous researchers. However, only averaged air-side heat transfer coefficients of entire heat exchangers can be acquired with this method. It is not possible to evaluate the heat transfer rates locally. Therefore, with the increasing depth of heat transfer research and complexity of heat exchanger geometry, local heat transfer and visualization methods are desired. There are three main directions to acquire local heat transfer coefficients experimentally: via temperature measurements, through flow velocity measurements and through mass transfer measurements.

1.2.2 TLC and IRT Method

According to Newton's Law of Cooling, if the temperature difference between wall and fluid is measured locally, the heat flux is controlled and assumed as constant, local heat transfer coefficient could be calculated. So, surface temperature measurement is the most straightforward method to acquire local heat transfer coefficient. There are several temperature measurement methods: thermocouples, thermochromic liquid crystal, and infrared thermography. Thermocouples have connection wires which can interfere with air flow. Therefore, non-intrusive methods are more suitable for air-side temperature measurement, especially for complicated geometries. Thermochromic liquid crystal (TLC) is a material which encounters molecular structure change when temperature varies. When illuminated with white light, TLC selectively reflects monochromatic light whose wavelength is a function of temperature. With increasing temperature, the observed color changes from red to blue in the visible range. In heat transfer applications, a thin film coating of TLC can be sprayed on the solid surface of interest, so global temperature mapping of the entire surface can be achieved. Kakade *et al.* (2009) investigated several TLC materials of different bandwidth to generate the correlations between hue and temperature. They also investigated factors which impact the accuracy of the measurement. The bandwidth of TLC materials, coating thickness, illumination, optical path, viewing angle, and aging are considered and tested. They concluded that with the mixing of several TLCs with different bandwidth, in conjunction with a careful calibration process, good accuracy could be reached for their purpose to measure the rotating disc in an air-cooled turbine. Because of its low cost and simple visualization, this method is widely used for local air side heat transfer research. Infrared Thermography (IRT) utilizes an infrared camera instead of TLC coatings to correlate color and temperature, which is more convenient for surface temperature measurements. The working principle of the infrared camera is based on radiation theory. The sensor detects electromagnetic energy radiated in an infrared spectral band by an object. Compared to TLC, the elimination of coatings minimizes the negative impact on airflow. Astarita *et al.* (2000) presented a review of infrared cameras based approaches when applied to convective heat transfer research. It was shown that it is suitable for simple and complex, as well as internal and external flow investigations in different areas. Moreover, with the technical development and cost reduction of infrared cameras, this method is widely used in many research areas. Li and Hrnjak (2015) applied IRT to observe surface temperatures of a microchannel heat exchanger to evaluate refrigerant distribution inside the heat exchanger. Bougeard (2007)

applied IRT to acquire air-side local HTC of a scaled-up fin and tube geometry in the wind tunnel. However, the accuracy of IRT camera is influenced by the radiation properties of the emitting surface and its surroundings. Therefore, both TLC and IRT require *in-situ* temperature calibration which generates inconvenience and limitations.

1.2.3 PIV Method

The Particle Image Velocimetry (PIV) method was developed to provide accurate, quantitative measurements of fluid velocity. Since convection occurs with bulk flow movement, by measuring flow velocity and applying correlations, the heat transfer coefficient can be determined. PIV method introduces tracer particles to the fluid which are assumed to have the similar motion behavior as the fluid. By exposing the particles to illumination, the velocity vectors of the particles could be recorded by a camera and subsequently translated to velocity profiles. Adrian (2005) summarized milestones of PIV during the past twenty years. From his review of past, current and future PIV technique trends, it is not hard to recognize that the PIV method is an expensive and extremely complicated system. The accuracy and precision of velocity measurement rely on seeding particles, illumination options, cameras, data interpretation methods, and computation devices. Particle selection is a demanding process because they are expected to represent fluid velocity. It means the particles to be selected will have no impact on fluid properties and no interaction with each other. Based on this requirement, the particles for air flow measurements are only microns in diameter which require intensive laser illumination to observe and acquire clear images. Aside, a sophisticated digital camera is also necessary to record high-resolution spatial particle motion with low noise. Furthermore, complicated image or video interpretation methodology require high levels of professional skill and experiences. Although commercialized PIV facilities are available, the application is still limited.

1.2.4 Naphthalene Sublimation Method

Naphthalene sublimation method is based on heat and mass transfer analogy which permits local heat transfer data to be experimentally acquired by local mass transfer measurements. The mass transfer boundary conditions are analogous to isothermal and adiabatic walls in convective heat transfer. It has been widely used in a variety of experiments since the 1950s. In a review paper from Goldstein & Cho (1995), the detailed process of naphthalene sublimation method is explained. The process is to have naphthalene coated on a solid surface of interest; then the weight and surface contour of the sample is measured; later the sample will be located in a wind tunnel which has air flow passing through; finally, the weight and surface contour are measured again to calculate the differences. Thereby, time-averaged local mass transfer data is acquired. If the concentration gradients and mass flux are analogous to temperature gradients and heat flux, the Sherwood number is approximately equal to the Nusselt number. They also pointed out limitations of this method including low and high flow velocity limitations, change of shape issue and sample coating challenges. Mendes (1991) reviewed specific heat transfer questions which applied naphthalene sublimation method. Examples include forced external air flow, laminar duct or channel flow, natural convection, fins and heat exchanger, impinging jet, rotating transfer surface and electronic cooling. It shows that this method is widely accepted and versatile in many engineering areas. DeJong and Jacobi (1996) employed this method to quantitatively acquire local Sherwood number and HTC of parallel-plate arrays. Kearney and Jacobi (1996) investigated and compared heat transfer of in-line and staggered, annularly finned tubes. However, the disadvantages such as toxicity of naphthalene, the complexity of coating, the difficulty of measuring surface contour on complicated geometry with a tip gauge make this method nowadays unfavorable among researchers.

2. METHODOLOGY

2.1 Principle of the Novel Visualization Method

The novel visualization method introduced in this paper also employs the analogy of mass and heat transfer, similar to the naphthalene sublimation method. As shown in Figure 1, a thin film coating of a specific acidic material is applied on a metal surface; a tracer gas and air flow are mixed sufficiently and pass across the coated sample. The coating material is specially developed, so it selectively absorbs tracer gas and changes color continuously as the reaction between coating and tracer is occurring. Therefore, convective mass transfer takes place as the tracer gas is transferred from the flow and absorbed by the coated surface. The acidity coating and tracer gas are working in pairs according to their chemical characteristic. Ammonia is used as the tracer gas because the absorption capability between the coating material and ammonia is the best. To minimize the corrosion on metal samples, the concentration of ammonia is controlled at a very low level which is only 50 ppm. Moreover, the corrosion risk will be evaluated during the experiment. If it is not negligible, other tracer options will be considered.

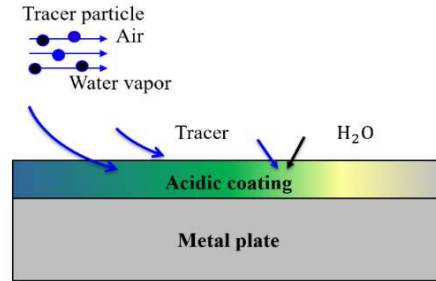


Figure 1: Principle of the novel visualization method

2.2 Analogy Theory and Boundary Layer Conditions Assumption

The conditions to apply the analogy between mass and heat transfer here are:

Governing equations such as continuity and momentum equations are the same for the heat and mass transfer processes. Mass transfer boundary conditions are analogous to isothermal and adiabatic walls in convective heat transfer. Concentration gradients and mass flux are analogous to temperature gradients and heat flux.

The concentration of tracer is only 50 ppm which has a negligible impact on the main air flow. Thus, the mass transfer of the tracer will not impact the density and velocity of the main flow. The continuity equation is the same. For the momentum equation which follows a similar dilute gas mixture logic also has the same format.

Considering the impacts on the velocity profile, this method is superior to the naphthalene sublimation. Comparing to naphthalene sublimation method, there is no deformation of the thin film coating. The coated surface is flat and smooth. Aside, roughness and evenness of the coating are similar to the original metal surface. Therefore, the coating is not expected to substantially influence shear stress at the surface. It is assumed that flow pattern and velocity profile will not be influenced by the presence of the coating.

A schematic showing the mass transfer boundary layer is shown in Figure 2. The interactive surface or coated surface is defined as the wall for future explanation. The figure assumes laminar flow passing across a flat plate. In the mass transfer experiment, there is no temperature difference between the fluid and the wall, representing an isothermal and adiabatic convective mass transfer process. The temperature boundary layer is shown here is just for reference. The main air flow cannot be absorbed by the wall, so a no-slip and impermeable wall boundary conditions is applied.

It is assumed that the free stream flow velocity is constant at U_∞ and zero at the wall. Flow velocity varies from zero to U_∞ in the boundary layer. The concentration profile in the mass transfer boundary layer is similar. If the tracer gas is evenly mixed in the air flow, the tracer concentration in the free stream flow is also a constant. The free stream concentration is assumed to be $C_\infty = 50 \text{ ppm}$. The rate at which the tracer gas is absorbed by the surface through a chemical reaction is much higher than the rates at which mass diffusion takes place. Therefore, it is reasonable to assume that the tracer concentration at the wall is zero. Consequently, the tracer concentration also varies from zero to C_∞ in the boundary layer. Due to the similar formats of the governing equations and boundary layer conditions, it is suitable to apply the heat and mass transfer analogy in this case.

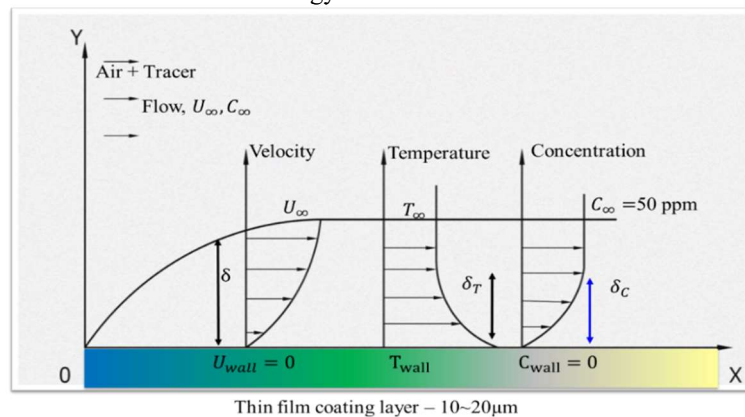


Figure 2: Boundary conditions of the novel visualization method

The similarity of heat transfer and mass transfer can be expressed by the following equations. From Newton's Law of Cooling for convective heat transfer shown in Equation (1), 1D local heat transfer coefficient h_{cx} , could be determined by measuring local heat flux q_x and temperature difference ΔT_x which can also be represented by Nusselt number Nu_x as shown in Equation (2). X is the distance in flow direction and k_f is the thermal conductivity of the fluid.

$$h_{cx} = \frac{q_x}{\Delta T_x} \quad (1)$$

$$Nu_x = \frac{h_{cx} \cdot X}{k_f} \quad (2)$$

Similarly, for convective mass transfer, the local mass transfer coefficient h_{mx} , can be expressed through Fick's law of diffusion. It is shown in Equation (3) and the local mass transfer coefficient can be calculated if local mass flux \dot{m}_x and concentration difference ΔC_x are measured. The local Sherwood number, Sh_x is used accordingly in Equation (4). D is the binary diffusion coefficient of ammonia-air.

$$h_{mx} = \frac{\dot{m}_x}{\Delta C_x} \quad (3)$$

$$Sh_x = \frac{h_{mx} \cdot X}{D} \quad (4)$$

It is well known that both Nusselt and Sherwood number are functions of the Reynolds number which is shown in Equation (5) and Equation (6).

$$Nu_x = f(Re_x, Pr, x) \quad (5)$$

$$Sh_x = f(Re_x, Sc, x) \quad (6)$$

$$Nu_x = Sh_x \left(\frac{Pr}{Sc}\right)^n \quad (7)$$

Therefore, by simply dividing the Prandtl number by the Schmidt number, the coefficient of the analogy can be calculated as shown in Equation (7). For laminar flow across a flat plate $n = 1/3$. Pr is the Prandtl number, which is the ratio of viscous diffusion rate to thermal diffusion rate of convection. Since the tracer gas concentration is extremely low, it can be assumed that the Prandtl number is equal to that of air which is about 0.71 at 25°C. Sc is the Schmidt number which is the ratio of viscous diffusion rate to mass diffusion rate between the tracer gas and air as shown in Equation 8.

$$Sc = \frac{\mu}{\rho \cdot D} \quad (8)$$

In this application, the tracer gas is ammonia which has 50 ppm concentration in the air flow. So, the dilute gas condition is fulfilled allow to use air viscosity and density to calculate the Schmidt number. The diffusion coefficient of ammonia in air is a known property and the Schmidt number is calculated to be approximately 0.78 at 1atm, 25°C. Therefore, Equation 7 could be converted to Equation 9 and 10.

$$\left(\frac{Pr}{Sc}\right)^n = \left(\frac{0.71}{0.78}\right)^{1/3} \approx 1 \quad (9)$$

$$Nu_x \approx Sh_x \quad (10)$$

Therefore, if the local mass flux can be measured, the local mass transfer coefficient can be computed. By applying the heat and mass transfer analogy, the Nusselt number is equal to the Sherwood number for laminar external flows across flat plates. Because of this analogy local heat transfer coefficients can be determined from the local Nusselt number.

3. EXPERIMENTAL METHODS AND SETUP

Step 1: Metal Samples

Aluminum 3003, copper, stainless steel and galvanized-steel are common materials to make heat exchangers. Therefore, all these metals sheets are prepared and cut into 60 x 60 mm pieces. The small metal pieces are flushed with acetone to make the surface clean.

Step 2: Prepare Coating Solution

The coating material can be diluted by mixing it with ethanol. Different coating solutions are made with 1:1, 1:2, 1:4 and 1:8 ratios between coating solution and ethanol.

Step 3: Coating Experiment

The coating material is a hydrophilic solution which spreads well on metal surfaces. Both dropping and dipping methods work. To quantify the solution used for coating the samples, dropping method is more preferable. A certain amount of solution is dropped on the metal surface. The sample is then placed on a flat bench for 30 minutes at room temperature for the coating to spread evenly

Step 4: Surface Measurement

The thickness and roughness of the coated surface is the main interest. The roughness of the coating can be measured by surface profiler. Both a non-contact 3D surface metrology Keyence VK-X1000 and a contact Dektak 300 surface profiler were used and compared. To measure the thickness, one corner of the coating is removed when the samples are still wet.

4. EXPERIMENTAL RESULTS

4.1 Coating Experimental Results

As shown in Figure 3, the metal plates are coated with 1:2 solution by dropping 1 ml solution on the metal surface. After waiting for 30 minutes at normal room temperature, the coated surfaces have dried and exhibit a yellow color. The coating experiments with other solution ratios show very similar results.

Metal samples before coating



Metal samples after been coated – dry surface

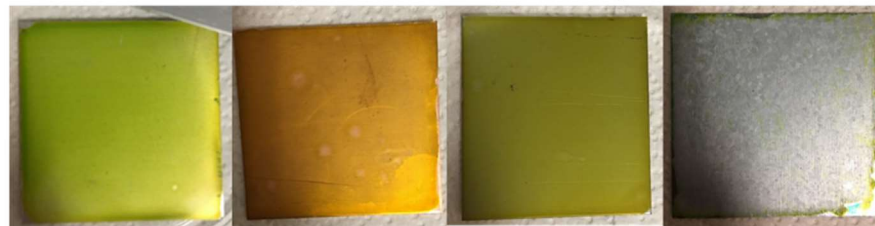


Figure 3: Coating on different metals (1:2 solution)

4.2 Surface Measurements

Figure 4 shows an aluminum plate which was coated with 1:1 ratio solution and scanned by a 3D surface metrology. The measurement range of this device is very broad (0.5 nm to several mm). To measure the coating thickness, the upper-right corner of the coating is removed when it is still wet. This method will have some coating accumulated at the interface due to the surface tension of the liquid solution. About 0.8 mm² surface area is scanned which covers both the coated and uncoated area. As shown in Figure 4, the average coating thickness at the interface is more than 60 μm, but only 8 μm at the inner location. So, the edge of the coating will not be considered. The coated surface observed is relatively even and thin.

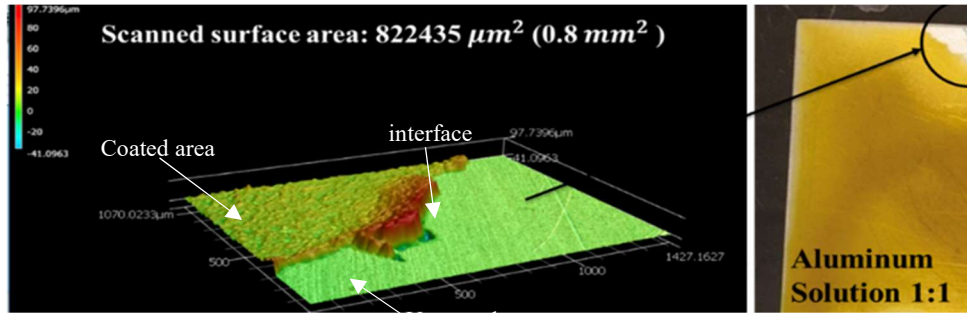


Figure 4A: Surface scanning of a coated aluminum surface with 1:1 ratio solution

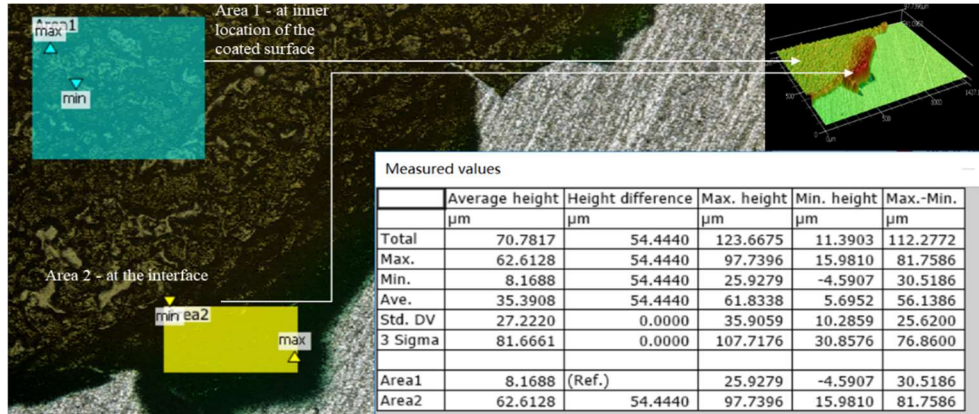


Figure 4B: Height comparison between inner coated area and interface

Also, quantitative measurements are taken to evaluate roughness. Ra is used to represent roughness of the surface which represents the arithmetic mean deviation of the assessed profile. This is the most common method to evaluate roughness. Both coated and uncoated surface roughness is measured. For each side, a linear measurement is taken which travels 280 μm to get roughness profile. For each sample at least 5 different locations were measured, and the results were found to be very consistent. As shown in Figure 5A and 5B, Ra of the coated surface is approximately 3.5 μm and the base metal is about 0.5 μm in one of the measurements.

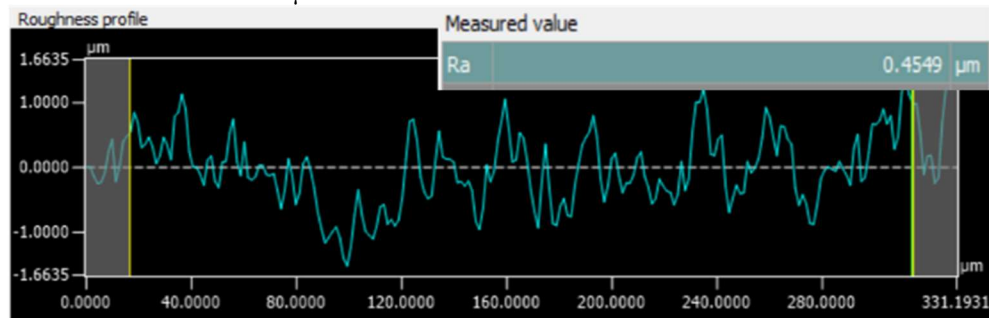


Figure 5A: Roughness measurements of uncoated surface

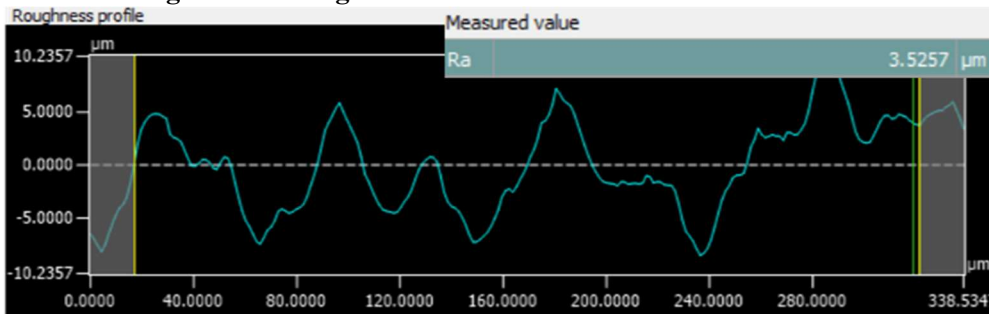


Figure 5B: Roughness measurements of coated surface (1:1 solution)

The metal plates that were coated with different solution ratios were also measured and compared. The averaged results are shown in Table 1.

Table 1: Summary of roughness and thickness measurement

Sample ID	Material	Material roughness Ra [μm]	Sample area [m^2]	Ratio of Coating solution	Coating method	Surface roughness Ra [μm]	Coating thickness [μm]
AS # 01	Aluminum	0.88	0.0036	1:1	dropping	3.51	8.7
AS # 02	Aluminum			1:2		1.02	8.0
AS # 03	Aluminum			1:4		0.79	7.1
AS # 04	Aluminum			1:8		0.99	7.0

Comparing with the 1:1 solution ratio, the roughness of the coated surfaces of the other solution ratios are reduced to approximately $1 \mu\text{m}$. The coating thickness of all samples is relatively constant at $10 \mu\text{m}$ the level. The coating is thin and shows good evenness. Therefore, little impact on the air flow during the mass transfer experiments is expected. Figure 6 shows surface measurements obtained with a contact Dektak 300 surface profiler. After the samples are located on the table manually, the probe contacts the sample surface and travels a certain distance (approximately 1 mm) to measure the hills and valleys. When the probe travels across the coated and uncoated surfaces, the coating thickness can be acquired. Similarly, the thickness at the interface/edge should not be considered because the measured thicknesses are not representative at those locations.

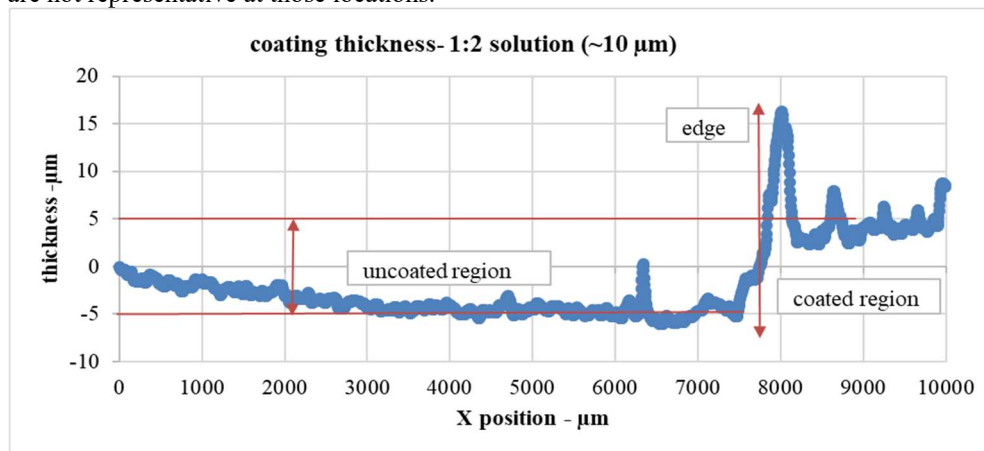


Figure 6: Roughness and thickness at 1:2 solution ratio (Dektak)

4.3 Color Change Observation on an Aluminum Plate

The coated samples with different solution ratios are stored at different environments. Samples were stored in a sealed plastic bag, in normal open-air conditions in the lab, and in a high humidity flask before they are compared. There is no difference between the sealed and the open-air storage after 2 months by appearance. Subsequently, these samples are tested in a closed container which has tracer injected to observe the color change. Both samples change their color from yellow to green to blue as desired, because the coating materials are active and react with the tracer gas. This proves that there is no demanding requirements related to the storage of the coated samples.

A stationary experiment was applied to observe the characters of color change. The coated sample of 1:2 solution ratio is sealed and located in a transparent container (100 x 120 mm), 0.3 ml ammonia and ethanol mixture (liquid) which has 15% ammonia concentration is positioned on the upper right corner. The ammonia particles will transport from the liquid to the air in the container by nature diffusion. The coated surface will absorb ammonia particles in the air and change its color. Figure 7 shows the color change happened at the upper right corner first because the ammonia solution is located there. The concentration of ammonia gases is higher at that location due to the nature of diffusion. With the time goes, the concentration of ammonia gas becomes uniform in the container, so the color of the coating has become uniform as well. The process is continuous and takes approximately 10 minutes to complete. The speed of color change can be controlled by the ammonia concentration, coating solution ratio, and flow velocity.

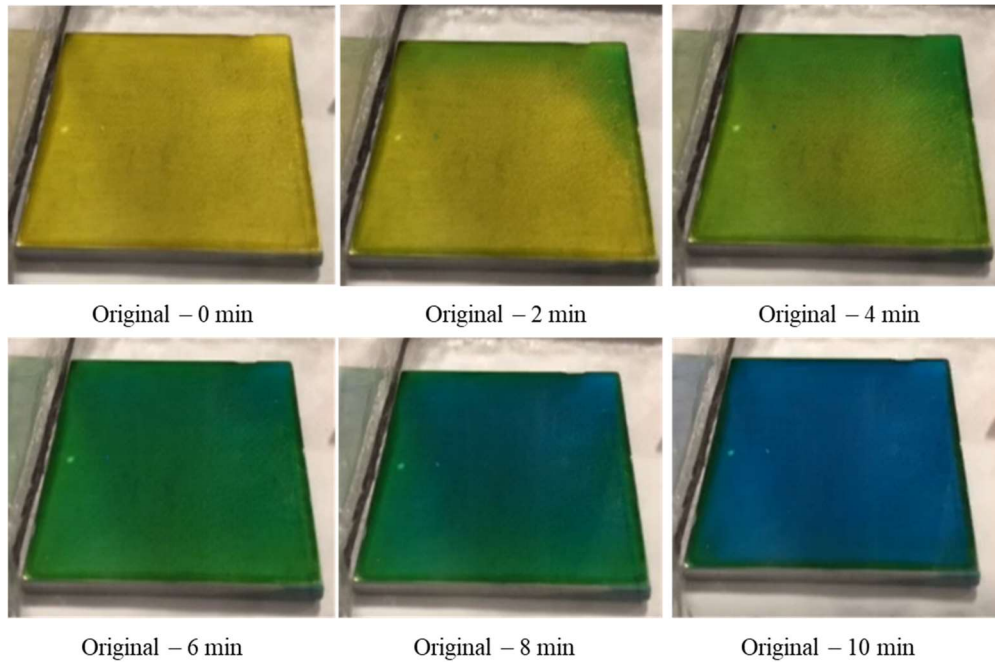


Figure 7: Color change process when ammonia tracer gas reacts with the coating

5. CONCLUSIONS AND FUTURE WORK

A new method to quantify local air-side heat transfer coefficients is being developed and this paper describes preliminary investigations required to establish the new method. The coating material is compatible with common metals such as aluminum, copper and stainless steel. The roughness of the coated surface is similar to the base metal. The thickness of the coating is about 10 μm which is expected to have a small impact on the air flow. The color change is a continuous process. The most important conclusion is the heat and mass transfer analogy can be applied, the experimental results verified the assumptions as expected. The new method is promising for local HTC evaluation. Convective mass transfer experiments with simple geometries need to be done first to check whether the results are same as obtained in previous local HTC studies. This will serve as validation for the newly proposed method. Several steps for future research have been identified.

- 1) Optical method for color calibration to acquire correlations between color change and ammonia mass flux.
- 2) Compare HTC with existing mathematical and experimental data for simple geometries
- 3) Investigate parameters which may impact the results such as humidity ratio, ammonia concentration, etc.
- 4) Apply coating and mass transfer experiments to more complicated surfaces and geometries

Although this method appears to have many advantages over existing methods suitable to determine local HTCs, there still a number of challenges that need to be overcome prior to being able to apply this intriguing visualization-based method to examine entire heat exchangers.

NOMENCLATURE

Symbols and Abbreviations

HTC	Heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)	q_x	1D heat flux at location x (W m^{-2})
TLC	Thermochromic liquid crystal (-)	h_{cx}	1D local heat transfer coefficient at x ($\text{W m}^{-2} \text{K}^{-1}$)
IRT	Infrared Thermography (-)	ΔT_x	Local temperature difference at x (K)
PIV	Particle image velocimetry (-)	L	Characteristic length (m)
Nu_x	Local Nusselt number (-)	k_f	Thermal conductivity of the fluid ($\text{W m}^{-1} \text{K}^{-1}$)
Re_x	Local Reynold number (-)	h_{mx}	1D local mass transfer coefficient at x ($\text{kg m}^{-2} \text{s}^{-1}$)
Sh_x	local Sherwood number (-)	m_x	1D mass flux at location x ($\text{kg m}^{-2} \text{s}^{-1}$)
Pr	Prandtl number (-)	ΔC_x	Local concentration difference (kg m^{-3})
Sc	Schmidt number (-)	D	diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)

n/N	Coefficient or correlations (-)	U_{∞}	Free stream flow velocity (m s^{-1})
VFD	Variable speed drive (-)	C_{∞}	Concentration of free stream flow (kg m^{-3})

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