Investigation of heat transfer coefficient of spherical element using infrared thermography (IR) and gas - water droplets (mist) as working medium

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Abstract. The changes that do occur in the air ambient properties with increasing concentration of water mist (fog) have a significant influence on heat exchange process between the building and the surrounding medium. In the present paper, the average and local heat transfer coefficient was estimated from surface temperature data obtained using infrared (IR) thermography. In particular, the experiments were performed on steady-state conditions under constant heat flux for a single sphere suspended in cylindrical channel using air as well as air / water droplets as working fluid. The influence of the different factors such as Re numbers and water flux density on heat transfer behaviors are examined. Five cases are tested under range of water flux density (0 - 111.68 kg m^{-2} hr^{-1}). The experimental results confirmed that the heat transfer coefficient significantly increased with increase in water flux density. The heat transfer coefficients are respectively 1%, 19.7%, 90.2% and 134% higher than those in air-cooling. The results also revealed that infrared (IR) thermography it has proven to be very efficient in measuring the surface temperature distribution. The results obtained by infrared thermography (IR) are compared with calibrated thermocouples and the temperature distribution is found to be in close agreement with 2.94% average error.

1. Introduction
The changes that do occur in the air ambient properties with increasing concentration of water mist (fog) have a significant influence on heat exchange process between the building and the surrounding medium. The presence of water mist in a flow of gas provides an excellent technique of heat transfer enhancement for many industrial applications [1-2]. The heat transfer enhancement mechanisms of gas-water mist flow include both, the effects of water mist momentum on gas main flow and evaporation of water droplets. This technique offers extremely important increase of heat and mass transfer rate between the surface and main flow due to the following features: absorbs a large amount of energy in the form of latent heat during the evaporation process of water droplets, increase specific heat of mixture and increase the turbulence into main flow and inside the boundary layer [3-4]. Numerous experimental and numerical investigations on heat transfer enhancement of gas-droplets two phase flow have been conducted. Most investigations are found deal with topics of heat transfer such as flat plate heated wall, turbine blades and heat exchangers. As was shown by literature review on the experimental and theoretical research of gas-droplets flow [1-10], the single-phase heat transfer
performance can be enhanced up to 70% by dispersed water mist in gas flow. The effect was manifested in a decrease in the surface temperature at simultaneous increasing of water mist concentration in the main flow. The literature survey points that all the experimental studies till date are based on thermocouples as one of the conventional devices that most frequently used to measure the temperature profile. Although that thermocouples can be accurately determine the temperature, but it is only a single/local point measurement, i.e., it is not capable of mapping temperature distribution at object surface. Also conventional measurement devices are not applicable when the electromagnetic heating induction is used, which creates eddies that lead to heat the temperature measurement devices itself. This will lead to a signal that does not precisely depict the temperature field being measured. Obviously, the direct method is hard to meet the requirements of engineering application. So, in the present paper, a non-invasive technique has been proposed to measure the surface temperature distribution and evaluate average and local heat transfer coefficient of spherical element using Infrared thermographic technique that can be used in practice. In recent year, Infrared thermographic temperature measurement has gradually become the most widely used measurement technique in industry, medicine, scientific research and military technology with many clear advantage of contactless measurement, remotely monitored, flexible, visual measurements in image, accurate and wide temperature range [11-14]. In addition, direct surface temperatures were recorded using K - type thermocouples for comparison to the Infrared (IR) thermography. Herein, the copper calorimetric sphere suspended in cylindrical channel was used as heated surface. The influence of water flux density (fog concentration) on heat transfer coefficient was studied at range of Reynolds number under constant heat flux. by using infrared thermography (IR) measurement system, the non-uniform local surface temperature and heat transfer coefficient were estimated.

2. Experimental Set-up and Procedure
The schematic diagram of the experimental set-up and details drawing of heat transfer test model are presented in figure 1 and figure 2. The experimental facility consisting of air subsystem, test object, droplets liquid subsystem, Infrared (IR) thermography digital camera and data acquisition system. The air subsystem consists of transparent Plexiglas channel having a circular cross section of 50 mm diameter; 3 mm thickness wall is set vertically. An electrical air blower was used with variac voltage regulator to control airflow velocity. On the same axis, a pitot tube flow meter (compact type) with digital manometer was used to measure the mean flow velocity. The measured object is a copper calorimetric sphere 34mm in diameter inserted in flow main stream and it is rear supported by a low thermal conductivity textolite rod ( k= 0.023 W/m °C, 4mm-diameter) which span across the Plexiglas channel. The test sphere was independently heated using 100W - high density cartridge heater having 8mm-diameter and 31mm-length. The surface temperature was directly measured using two calibrated thermocouples (K-type) were inserted inside the copper sphere in positions indicated by the numbers 1, 2 as shown in figure 2. All thermocouples are connected to multichannel data acquisition system that consists of analog signal input module OWEN MV110-8A and MSD200 data logging unit. The droplets liquid system was a 1.7 MHz ultrasonic atomization has the same structure as the one reported in ref. [15]. The droplets liquid generator consists of a piezoelectric transducers, transparent vessel, water tank and blower fan. The water mass flow rate was measured by the mass of water passing a droplets generator subsystem per unit time. To blend the liquid droplets with a controlled amount of air, a mixing chamber was installed and used as the blender. For contactless measurement, we used an infrared (IR) camera with a 320 x 240 pixel image dimension, and a 0.1m standard lens. Under constant temperature condition in the laboratory, the position and the focal length of the infrared (IR) camera are adjusted and aimed at the test object inside channel as shown in figure 1.
Infrared (IR) measurement system gives a temperature distribution signature on the surface of sphere being measured as shown in figure 3. This will extensively help in understanding the influence of water droplets evaporation on heat transfer behavior.

In steady-state condition, the average surface temperature module as shown in figure 4 is recorded by the infrared (IR) measurement method to compare with the data obtained by thermocouples. For the purpose of validating the measurements made by infrared (IR) measurement method, experiments are carried out to estimate the surface temperature and heat transfer rate using contact-thermocouples method. Repeating the above process in the measurement of other cases of water flux and Re numbers, the final results are shown in figure 4. Indeed, if we regarded that thermocouple readings as true and reference temperature of sphere being measured, then Accordingly, the experimental data: the average error of infrared (IR) temperature measurement method is 2.94%.
3. Mathematical formulation
This paper focuses on determination the average and local heat transfer rate in smooth sphere using infrared (IR) thermography with air as well as air / water droplets as working fluids. The uniform heat flux can be calculated by [16].

\[ q = \frac{Q_{el} - Q_{los}}{A_s} \]  

(1)

where \( Q_{el} \) – the overall heat generated by the electrical cartridge heater, \( Q_{los} \) – the heat loss obtained by measuring the average surface and the surrounding temperatures and estimated as 2.5% of the overall heat supplied. The local values of the heat transfer coefficient were obtained from [17].

\[ h_s = \frac{q}{(T_{x,fs} - T_{ai})} \]  

(2)

where \( T_{x,fs} \) – the local sphere temperature recorded by infrared thermal imager. For a single phase - air coolant, the average heat transfer coefficient can be estimated as [17]:

\[ \bar{h} = \frac{q}{(T_{av,ts} - T_{ai})} \]  

(3)

where \( T_{av,ts} \) – the average surface temperature obtained by the thermocouples readings indicated by the numbers 1, 2 as shown in figure 2. The average heat transfer coefficient for the air/water droplets flow can be estimated by using the wet bulb temperature at the inlet of the test section as the reference temperature that is [17]

\[ \bar{h} = \frac{q}{(T_{av,ts} - T_{mi})} \]  

(4)

\[ T_{av,ts} = \sum T_{x,ts} / n \]  

(5)

Based on the capillary wave mechanism, the droplet diameter can be calculated using Lang equation [18].

![Figure 4. Comparison of surface temperature measured by infrared (IR) thermography and the surface temperature measured from thermocouples during verification tests](image)
\[
d_p = 0.34 \left( \frac{8\pi\sigma}{\rho F^2} \right)^{1/3}
\]

The Reynolds number was obtained from [19]

\[
Re = \frac{m_a D}{\mu A}
\]

The heat transfer performance can be defined as the ratio of the heat transfer coefficient of air/water droplets flow to that of a single phase flow at constant pumping power. It can be written as [20]

\[
\eta = \frac{h_{mist}}{h_{air}}
\]

4. Experimental results and discussion

4.1. Infrared experimental results of air/water droplets flow

In this paper, two modules have been mainly studied for air/water droplets flow using Infrared (IR) temperature measurement system, the surface temperature measurement module and the heat transfer estimation module. The surface temperature plays an important role on heat transfer process. The distribution of local surface temperature over the surface of sphere as a function of diameter under different water flux is depicted in figures 5. It can be seen that the surface temperature tends to decrease gradually as water flux increases for constant surface heat flux. The surface temperature decreases about 5.5%, 20.2%, 37.6% and 49.4% compared with air - cooling under different water flux. It can be expressed by the evaporation phenomena on the sphere surface that leads to absorb a large amount of energy in the form of latent heat during the droplets evaporation process.

In the figures 6 the local heat transfer coefficient was related as a function of sphere diameter under range of water flux density. It can be observed that the effect of water flux density on heat transfer rate is significant for range of Re numbers. Using air/water droplets technique results in an enhancement of the heat transfer rate over air alone. The heat transfer mechanism may include three important physical effects: the convective heat transfer based on a decline temperature gradient, water mist evaporation on the heating surface and sensible heat of impinging water mist.
4.2. Direct measurement experimental results of air/water droplets flow

In the figure 7, the average surface temperature was related as a function of Re numbers under range of water flux density. It can be seen that the surface temperature tends to decrease gradually with increasing Re numbers. Also, it can be observed that the surface temperature decreases as water flux density increases. The surface temperature decreases about 4%, 17%, 37% and 47% compared with air – cooling under different water flux. In the figure 8, the dimensionless heat transfer performance was related as a function of Re numbers under range of water flux density. It can be seen that the heat transfer performance for all cases are generally more than unity and that indicate the effect of suspending water droplets into main flow on heat transfer behavior. At range of Re numbers (Re = 2500 - 10000), the heat transfer performance were in a range 1.0–1.26 for all water flux cases. This can be expressed that, when the surface temperature is hot (Ts >140), the water droplets may be completely evaporated before arriving to the heated surface due to the force of evaporation without wetting the heated surface. The heat transfer performance rapidly increases with increasing of water flux density for all cases of Re numbers. At Re numbers (Re = 47500), enhancement factor is 2.7 times of that with only air-cooling for water flux density (111.68 kg m$^{-2}$ hr$^{-1}$).

5. Conclusions

A steady heat transfer and temperature profile measurements method for spherical element based on infrared (IR) measurement system is proposed in this paper. Based on the experimental results, the main conclusions can be summarized as follows:

- The results revealed the need to take into account changes of moisture content in air ambient in the development of refined methods to calculation of heat supply systems of buildings and structures.
- The infrared thermography (IR) it has proven to be very efficient in measuring the surface temperature distribution. The results obtained by infrared thermography (IR) are compared with a calibrated thermocouples and the temperature distribution is found to be in close agreement with 2.94% average error.
- The air/water mist cooling it has proven to be very efficient technique in removing heat from heated sphere. The surface temperature decreases about 4%, 17%, 37% and 47% compared with air-coolant by using different water flux density.
- The heat transfer performance for all cases are generally more than unity indicating that the presence of water droplets with different water flux given more efficient heat transfer enhancement than the application of air-cooling.
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