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Comparative Study of Convective and Radiative Heat Transfer in Milliflow Reactors

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Nowadays, infrared emitters are mostly used in the food industry as drying method. However, there is also great potential for such heaters in flow chemistry. Flow reactors do not only require thermal efficiency but also accurate modulation of heat transfer. This can be achieved by the use of infrared emitters. In this research, the electrical efficiency of three different types of infrared emitters: short, medium and long wave, is determined. Next, these efficiencies are benchmarked against a convection oven which uses forced convection of hot air. In addition, the influence of surface absorptivity of the stainless steel is tested with and without a black coating. It was hypothesized that the black coating would enhance energy absorption. Similar trends in heat transfer were observed between the three different types of infrared emitters. When both convection and infrared heating used the same amount of electrical power and were both applied in the same convective setup, the net absorbed thermal power was 10 percentage points higher in the infrared setups than by convective heating. This indicates that the efficiency of transferring thermal energy to the liquid in a tubular reactor is higher for infrared heaters than for the convection oven. In addition, a black coating of the flow reactor improved the absorbed power with 6 percentage points. In conclusion, the infrared emitters are excellent for heating flow reactors with high absorptivity, and are more efficient than convection ovens.

1. Introduction

In many industrial processes, accurate temperature control is essential and needs thorough understanding of heat transfer mechanisms and properties. Among the three well known mechanisms of heat transfer, radiation is the least used one (Bergman et al., 2011) . The most popular heating systems for flow reactors are shell and tube heat exchangers with a liquid heat transfer medium and convection ovens which uses hot air (Subramanian 2014). Nowadays, chemical industry mainly uses shell and tube heat exchangers due to a high overall heat transfer coefficient. Typical overall heat transfer coefficient (U) values for shell and tube heat exchangers with water as liquid are between 850 and 1700 W/K m² (Yunus 2002). Other advantages are the ease of maintenance of the shell, flexible choice of heat transfer medium and robust design. However there are disadvantages, namely: the high cost of installation and repair, the large and heavy construction, the increase of the pressure drop due to the amount of small tubes and the heat transfer medium is limited to about 300 °C (Thakore and Bhatt, 2007; Shah and Sekulic, 2003; Nitsche and Gbadamosi, 2016). Some companies apply a convection oven with hot air as heat exchange medium due to the flexibility and ease of maintenance. A typical U-value for a convection oven, determined with heat flux sensors, is between 10 and 40 W/K m² (Carson et al.,2006). This is the main disadvantage of the convection oven in comparison with the shell and tube heat exchanger with a liquid heat transfer medium (Kreith et al., 2011). Shell and tube heat exchangers, with in the shell hot air and in the tubes cold water are comparable with heating of water in tubes which are placed in a convection oven. These heat exchangers have U-values between 30 and 60 W/K m² (Yunus 2002). Improving the efficiency of shell and tube heat exchangers is based on increasing the turbulence which has a positive effect on the heat transfer (Sriromreun and Sriromreun, 2018; Valdes et al.,

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2018; Pavel and Valenta Vaclac, 2014). In these heating systems, the most important heat transfer mechanisms are conduction and convection.
In contrast to the chemical industry, the food industry frequently uses infrared emitters, mainly for food drying (Pan et al., 2011; Mongpraneet et al., 2002). Infrared radiation (wavelength between 0.78 and 1000 µm) is absorbed by a surface and is transferred into heat. Infrared heaters have several advantages like: compact design, accurate temperature control and uniform heating (Sakai and Hanzawa 1994). It is interesting to use radiation as heat transfer mechanism since the heat transfer rate of radiation increases with the fourth power of the temperature of the heater surface. However, to the knowledge of the authors, no studies of heat transfer by infrared emitters towards flow reactors are available in literature. Flow reactors are mainly developed for hazardous chemical reactions, energy efficiency and for having a compact design (Watts and Haswell 2003). Therefore, the advantages of infrared heaters are expected to be high on these platforms. Infrared emitters can be divided into three types: short wave, medium wave and long wave, dependent on the wavelength of the emitted infrared waves. Short wave emitters have a fast response time (1 s), a peak wavelength of 1.2 µm with a corresponding temperature of 2000 °C and they are used in powder coating, adhesive bonding and as preheating. Next, medium wave emitters have a slower response time as short wave emitters (30 s). The peak wavelength for medium wave emitters is 2.2 µm and corresponds with 1000 °C. Medium wave emitters are used for drying and curing of food products. At last, the long wave emitters have a slow response time (> 300 s) and a peak wavelength of 4 µm with a corresponding temperature of 450 °C. The main application for a long wave emitter is heating nearby objects (Pan and Atungulu 2011). Response time is defined as the time which is needed for reaching the maximum temperature of the emitter. Radiation energy, emitted on a surface, can be reflected, absorbed (α) or transmitted, dependent on the type of the surface. A surface can be opaque, semi-transparent or blackbody. An opaque surface does not transmit radiation energy. When the surface is semi-transparent, the radiation energy is partly reflected, absorbed and transmitted. A blackbody completely absorbs (α=1) the radiation energy (Modest 2013). Next to the type of the surface, the properties of the surface material influence the absorption of the radiation energy. For example, the use of black coatings is beneficial for the absorption of radiation energy (Liebmann 2015). The aim of this study is to quantify the improvement of power absorption of radiative emitters versus a convection oven. In this research, a stainless steel (uncoated or black coated) tubular reactor is used with water as the medium inside the reactor to be heated.

2. Material and methods

A general sketch for all the experiments is shown in Figure 1. The difference between infrared and convection setups is in the heating section of Figure 1 and is explained later in this section.

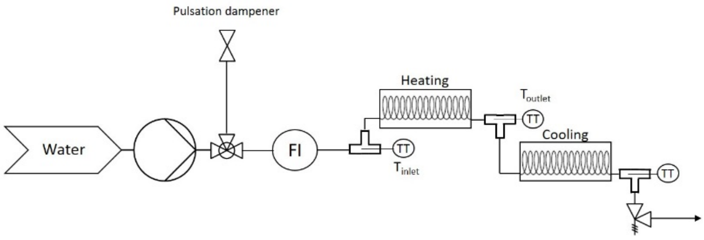

Figure 1: General setup with flow indicator (FI) and temperature transmitter (TT)

The setup consists of a Lewa LCA membrane pump which is frequency controlled with an Altivar ATV312 regulator. To eliminate the pulsations of the membrane pump, a pulsation dampener is added after the feeding pump. An ES-flow indicator of Bronkhorst measures the water flow rate of 56 ml/min which is logged with Labview. The PT100 temperature transmitters are logged with Labview and a NI9216 board of National instruments is used for transferring the data of the temperature sensors. The tip of the sensor is placed in the opposite direction of the flow with a Swagelok t-joint and has no contact to the wall of t-joint. The tubing of the setup is 316L stainless steel tubing and has an OD of 1/8", ID of 1.4 mm and a wall thickness, d_x of 0.889 mm. The conductivity of stainless steel is $k_{material}$ = 14.6 (W/m K). The pressure in the reactor was set with an adjustable pressure relief valve of Swagelok to keep water in liquid phase in all experiments. Demineralized water with a conductivity lower than 1.5 µS/cm and a thermal conductivity of k_{liquid} = 0.598 (W/m K) is used. The heat flow in the setup is determined with Eq(1).

$$Q_{absorbed}=\dot{m}C_p(T_{outlet}-T_{inlet}) \quad (1)$$

The heat flow $Q_{absorbed}$ (W) depends on the mass flow, ṁ (kg/s), the heat capacity, C_p (J/kg K) and the temperature difference between the outlet (T_{outlet}) and the inlet (T_{inlet}) of the flow reactor. In Eq(2), the heat flow is equal to the product of the overall heat transfer coefficient, U (W/m² K), the surface area, A (m²) and the logarithmic mean temperature difference, ΔT_{LM_global} (K). The logarithmic mean temperature difference uses the inlet and outlet temperature of the water and the environmental temperature around the tubing (T_{oven}). The overall heat transfer coefficient (U) is determined with Eq(2).

$$Q_{absorbed}=UA\Delta T_{LM} \qquad \text{with } \Delta T_{LM\_global}=\frac{(T_{oven}-T_{outlet})-(T_{oven}-T_{inlet})}{\ln\left(\frac{T_{oven}-T_{outlet}}{T_{oven}-T_{inlet}}\right)} \tag{2}$$

The thermal coefficient inside the tubing, h_{inside}, is due to convective heat transfer from the stainless steel reactor wall to the laminar flow of water (Reynolds number Re = 848). This thermal coefficient can be calculated with the Nusselt number and is h_{inside} = 1548 (W/m² K) (Paul et al., 2004; Bergman et al. 2011).

$$Nu=\frac{h_{inside}\, d}{k_{liquid}}, \qquad \text{For laminar flow and constant surface temperature: Nu = 3,66} \tag{3}$$

The thermal coefficient is used to determine the inner wall temperature of the stainless steel tubing, T_{wall_in}. Eq(4) depends on the mass flow, $\dot{m}$ (kg/s), the heat capacity, C_p (J/Kg K), the inner diameter of the tubing, D (m), the length of the tubing, L (m), the thermal coefficient inside the tubing, h_{inside} (W/m² K), the logarithmic mean temperature difference (ΔT_{LM_in}) between T_{inlet}, T_{outlet} and T_{inner_wall} and the temperature difference between T_{inlet} and T_{outlet}. While employing Eq(4) the inner wall was assumed to have the same temperature along the tubing. The fluid inside was assumed incompressible and the fluid properties were assumed constant.

$$h_{inside}=\frac{\dot{m}C_p}{\pi DL}\frac{T_{outlet}-T_{inlet}}{\Delta T_{LM}} \qquad \text{with } \Delta T_{LM\_in}=\frac{(T_{wall\_in}-T_{outlet})-(T_{wall\_in}-T_{inlet})}{\ln\left(\frac{T_{wall\_in}-T_{oulet}}{T_{wall\_in}-T_{inlet}}\right)} \tag{4}$$

The outer wall, T_{wall_out}, is calculated with Eq(5), taking the heat flow, Q (W), T_{wall_in}, d_x and the thermal conductivity of the material, k (W/m K) into account.

$$Q_{absorbed}=\frac{T_{wall\_out}-T_{wall\_in}}{d_x/k} \tag{5}$$

2.1 Comparison of the three types of infrared emitters

The specifications of the used infrared emitters are shown in Table 1. The setup (heating part in Figure 1) consists of an aluminum tube with four infrared emitters of the same type (red in Figure 2). Water is pumped through the 6 m stainless steel tube which is placed inside the aluminum tube. The power of the infrared emitters is set with an autotransformer coupled to a power meter (Voltacraft), which controls the voltage and the current. Four different powers (500, 1000, 1500 and 2000 W) are tested for each type of infrared emitter.

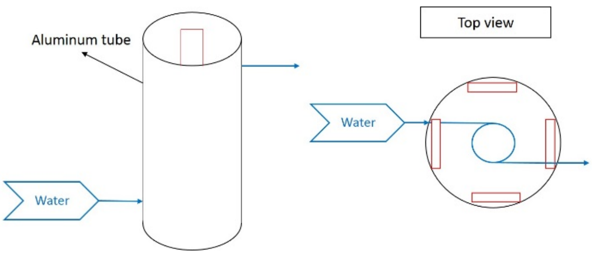

Figure 2: Setup for determination of the heating efficiency of the infrared emitters (red)

Table 1: Specifications of the infrared emitters

	Short wave emitter	Medium wave emitter	Long wave emitter
Company	Heraeus	Heraeus	IHP
Filament temperature (°C)	1800-2400	800-950	555
Maximum power (W)	1200	500	750
Total length and width (mm)	340 x 25	300 x 20	245 x 60
Response time (s)	1	60-90	/

2.2 Convection versus radiative heating

For benchmarking with a standard heating unit, a convection oven is used as the heating part in Figure 1. The oven is a Memmert Universal U75 oven and can reach 300 °C. The same stainless steel tubing, used for IR experiments, is attached inside the convection oven. Firstly, a test at 5 different powers of 650, 730, 840, 1171 and 1365 W was performed. These power levels were associated with the equilibrium oven temperatures of 100, 150, 200, 250 and 300 °C respectively. The radiation energy reflected by the walls of the oven is assumed to be low due to its low surface temperature and polished stainless steel wall of the oven which typically has a low emissivity of about 7% (Modest 2013). During all these tests, the fan of the oven ensures maximum forced convection inside the oven. The power levels are measured and logged with the Voltacraft power meter. Afterwards, two different types (short wave and medium wave) of infrared emitters were attached inside the convection oven to be tested in the same heat environment. Long wave emitters cause high temperatures in the environment, practically excluding them to be tested in the convection oven. The short and medium wave infrared emitters are tested at the same power levels as the convection oven with the fan continuously running. At last, the absorptivity of the flow reactor is elevated by a black coating.

3. Results and discussion

The absorbed powers of each setup are shown in Figure 3. In this figure the absorbed power (%) is expressed as the ratio of the actual power (W) versus the applied power (W).

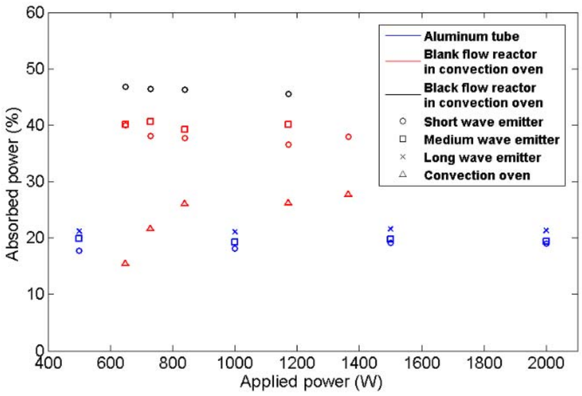

Figure 3: Absorbed power of short wave (○), medium wave (□), long wave (x) emitters and air convection (Δ) at different applied powers and with three different setups

Three different colors, blue, red and black in Figure 3 correspond to a particular setup. For the results in blue, the aluminum tube is used. The results show that there is negligible difference between the three different infrared emitter types and the applied power levels in a poorly insulated setup. All infrared heaters yield an efficiency between 18 and 22 % if only radiative heat transfer is taken place.

The results in red show the difference of convection heating and infrared emitters, which are placed in the convection oven, at different applied powers. There are two different trends visible in Figure 3. The absorbed power of the emitters is doubled (up to 40 %) when they are coupled with forced convection. This is partly due to the fact that the convection oven is better insulated than the aluminum tube. Nevertheless, it is visible that the infrared emitters, when they work in tandem with convection, are more efficient than pure radiation or pure convection. The heat transfer efficiency of the convection oven is nearly constant at higher applied powers (ca 30 %) but it decreases with lower applied powers.

Finally, a black coating on the flow reactor (black circles) increases the absorbed power with 6 percentage points compared to a blank flow (red circles) upon irradiation with a short wave emitter in the convective oven. It is known that the emissivity and absorptivity increase when a black coating is used and thus the absorbance of radiation energy is more efficient (Liebmann 2015). The absorption power ratio of all the experiments with infrared heaters follows a logical and continuous trend for varying input power as well as among black coated and uncoated trials confirming the validity of the experiments.

The graphs in Figure 4 show the temperature profiles from the inside of the flow reactor towards the environment for a convection oven, short and medium wave infrared emitter at 1171 W.

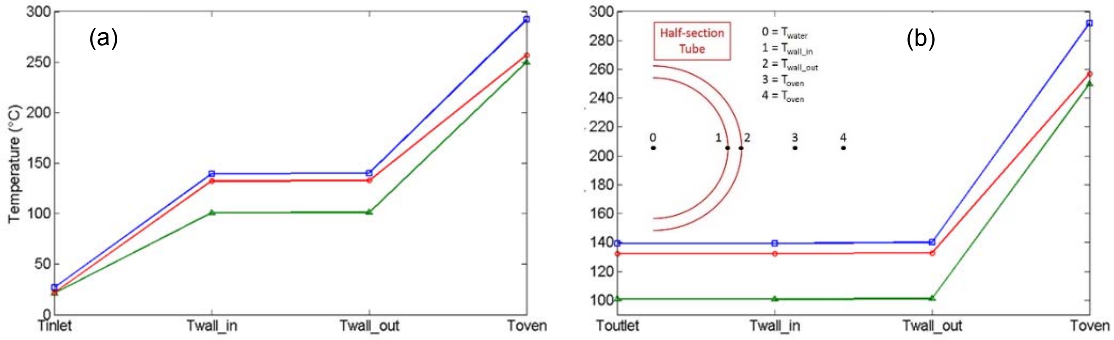

Figure 4: Temperature profile of convection oven (-Δ), short wave (-○) and medium wave (-□) emitter with a power consumption of 1171 W measured in the convection oven with inlet (a) and outlet (b) temperature

The heat flow is dependent of three different resistance factors as visible in Figure 4. T_{oven} is measured nearby the ceiling of the oven. T_{inlet} and T_{outlet} are used in Figure 4a and Figure 4b respectively for the temperature profiles. Figure 4a corresponds to the profile at the inlet (highest heat flux) while Figure 4b corresponds to the outlet conditions (no heat flux). Extra experiments needs to be conducted to determine at which point each reactor actually reaches the equilibrium. The other temperatures, T_{wall_in} and T_{wall_out}, are calculated based on Equation 4 and 5. The first resistance, from the T_{oven} to T_{wall_out}, is the highest of the three and the resistance is caused by radiation and forced convection of the hot air. However, it is visible that the temperature at the outer surface increases due to absorption of radiative energy when an infrared emitter is used resulting in higher efficiency. A decrease of only 0.5 °C between the outer surface and inner surface temperature is visible since stainless steel is an efficient conductor of heat. Therefore, the temperature loss, due to conduction, in the reactor is minimal. At last, Figure 4a and 4b shows a decrease in temperature between the inner surface and the water (T_{inlet} and T_{outlet}). Since the flow regime inside the flow reactor is laminar, the Nusselt number and thus the convection heat transfer coefficient is the same for both heating methods. The viscosity and density change of water at increasing temperature, has a negligible effect on the Reynolds and Nusselt number.
The overall heat transfer coefficient of the convection oven, short wave and medium wave emitters are calculated from the measured $Q_{absorbed}$ by Eq(2) and are shown in Figure 5.

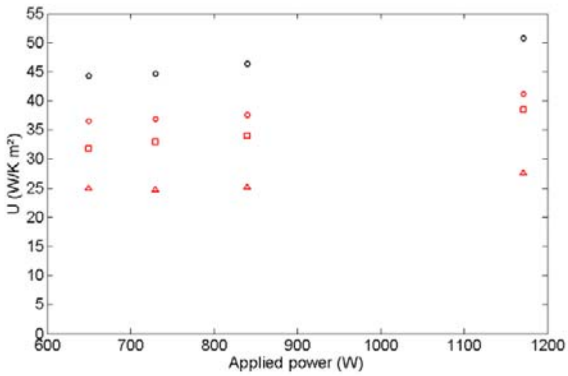

Figure 5: The overall heat transfer coefficient of short wave, with a blank (○) and black (○) reactor, medium wave (□) emitters and convection oven (Δ), each recorded under convective conditions at different applied powers

Figure 5 shows that the overall heat transfer coefficient is the lowest when the convection oven is used. This means that the resistance parameters are high and thus the heat flow is limited. The measured *U*-value is consistent with reported values for convection ovens in literature, typically between 10 and 40 W/K m² (Carson, Willix, and North 2006). The *U*-value can fluctuate throughout the oven dependent on the local velocity of the hot air. The difference in *U*-values between the short and medium wave emitters indicates a higher thermal resistance for medium wave emitters. This is mainly due to a higher environmental temperature (Figure 4), since differences in the absorbed power between the short and medium wave emitters are negligible (Figure 3). At last, the *U*-value for a black coated flow reactor is the highest at all applied powers. The *U*-value of the radiative emitters is much lower than the liquid-liquid shell and tube heat exchangers.

Nevertheless, infrared emitters are very useful because the heat transfer medium limits the maximal temperature to be applied by these heat exchangers. With infrared emitters, it is possible to reach a higher logarithmic mean temperature difference due to a higher environmental temperature. A higher logarithmic mean temperature difference results in a higher heat flow, Eq(2). In addition, the *U*-value in Figure 5 shows an increasing trend for all the setups when the applied power increases. A higher applied power causes a higher environmental temperature and thus a higher driving force for the flow of heat.

4. Conclusion

This study investigates the efficiency of heating a tubular flow reactor with short, medium and long wavelength infrared heaters, which use radiative energy solely or in combination with forced convection. These heaters are compared to heating by forced convection of hot air. The three different infrared emitters show a similar performance if only radiation is taken into account. When the short and medium wavelength infrared emitters were installed in the convection oven, the absorbed power is between 39-40 % which is 10 percentage points more efficient than the convection oven. It was also shown that the absorptivity is an important factor for the absorbance of the radiative energy. Heating a black coated tubular reactor with infrared emitters further elevates the heat efficiency by 6 percentage points compared to a blank stainless steel reactor. The obtained results show that radiation, particularly when coupled with convection, has high potential to be employed for flow chemistry especially for reducing reaction times by elevating the reaction temperature to extreme conditions. Therefore, this heating technique should be further explored to perform fast reactions at high reaction temperatures (>300^{0}C) that would otherwise require hazardous and/or expensive heating setups.

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