ISBN-978-989-9121-25-6
MILAN 24th International Conference on "Innovations in Science & Technology" (MIST-23)
June 14-16, 2023 Milan (Italy)

Flexible Thermal Convective Emitter - Unsteady Irreversibility Analysis

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Abstract: *The intensity of convective electric heating of the fluid is mainly determined by its volumetric flow, the installed power of the heater and the geometric characteristics of the channel through which it flows. The temperature of the surface of the heating source, and its power is limited by the maximum allowed value. The constant convective surface of the electric heating source, with the above limitations, results in a wide range of electric convective heaters. The thermal efficiency of these heaters depends on a case-by-case basis, while the temperature of the fluid varies in some intervals in relation to the required temperature that needs to be achieved. During fast transient fluid heating processes, convective electric heaters are thermally inert, low efficiency, while in some cases their application is unjustified. Therefore, the thermally generated entropy of the described convective heaters and fluids increases, from case to case, while their energy efficiency is minimized.*

Keywords: *Flexible Heater, Airflow, Entropy Generation, Entransy Dissipation, Modification Irreversibility Ratio.*

1. Introduction

The efficiency of convective electric heating of different fluids depends on several processes and geometric parameters of the analyzed heating source. Basically, forced convective heating is determined by its flow, the installed power of the heater, and the geometric characteristics of the channel through which the fluid flows. The flow of fluid inside a channel can be laminar or turbulent, which depends on the flow speed of that fluid and the geometric parameters of the channel through which the fluid flows. The surface temperature of the heating source and its output heat flux is limited by the maximum allowed value. For various technical applications, different fluids, and their process characteristics, the output heat flux of the heater varied. The reason for the above is that the fluid must promptly take over the obtained heat otherwise the heater will be either overheated or under-cooled. The constant convective surface of the electric heater with the mentioned limitations, results in a wide range of electric convective heaters. The thermal efficiency of these heaters depends on a case-by-case basis, while the temperature of the fluid varies in some intervals in relation to the required temperature that needs to be achieved, from [1] to [7]. During fast transient fluid heating processes, convective electric heaters are thermally inert, i.e. low efficiency, while in some cases their application is not justified.

Therefore, the thermally generated entropy of the described convective heaters and fluids increases, while their energy efficiency is minimized. It is precisely for the above reasons that the idea of flexible thermal convective emitters was arrived at, which enables minimizing the limitations and shortcomings of existing convective heating sources. The solution analyzed in this paper, the flexible thermal convective emitter, enables

https://doi.org/10.17758/HEAIG13.H0623109

the instantaneous change of the convective surface and the input power of the heater. Thermal irreversibility during convective heating of fluids, i.e. generated entropy and entransy dissipation ratio analyzed in this paper.

2. Methodology

2.1. Materials and Procedures

In order to minimize the thermal irreversibility of the analyzed heating system, Fig.1, an analytical model of thermally generated entropy was established. By minimizing thermal irreversibility, the possibility of maximizing the energy efficiency of the analyzed flexible convective emitter is established.

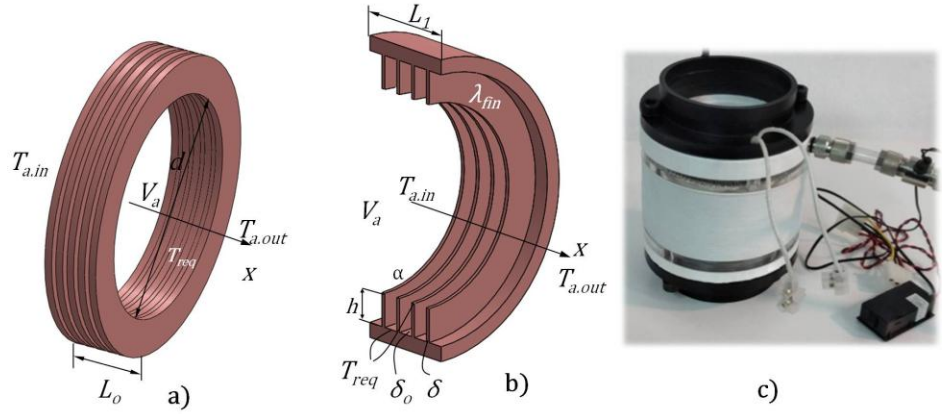

Fig. 1: Synchronized change of the convective surface and input power of the flexible electric heater enables optimal convective heating of the fluid at its constant flow.

Air enters inside the flexible convective emitter with mean velocity w_a and temperature $T_{a.in}$. The temperature of the inner surface of the convective emitter is limited by the maximum value T_{req}, which is considered constant in this analysis. The forced convective heat balance between the internal heating surface of the flexible heating emitter and the air can be represented by equation (1),

$$\rho_a w_a \frac{d^2\pi}{4} c_a dT_a = q_{req} d\pi dx \tag{1}$$

from which, after integration, the temperature of the air at the exit from the flexible thermal convective emitter is obtained

$$T_{a.out} = T_{a.in} + d\pi \frac{q_{req}}{\rho_a c_a V_a} x \tag{2}$$

The where α is the convective heat transfer coefficient, w_a is the mean velocity of airflow across the channel section, T_{req} is the required maximum temperature of the inner wall of the channel with diameter d. In the case that it is necessary to immediately heat the air to a higher temperature without the temperature of the inner surface of the channel not exceeding the required T_{req}, the flexible thermal emitter increases its surface many times over. The increase of the convective surface can be automatically regulated, so that the total exchanged heat inside the flexible connective emitter is represented by equation (3).

$$Q_{fins} = n_{fin}Q_{fin} + (n_{fin}-1)Q_{bfins} = n_{fin}(T_{req} - T_{a.in}) \left(\alpha P_{fin}\lambda_{fin}A_{fin}\right)^{0.5} tanh\left[\left(\frac{\alpha P_{fin}}{\lambda_{fin}A_{fin}}\right)^{0.5} h\right] + (n_{fin}-1)d\pi\delta_o\alpha(T_{req}-T_a) = q_{ref}\left\{n_{fin} \left(\frac{P_{fin}\lambda_{fin}A_{fin}}{\alpha}\right)^{0.5} tanh\left[\left(\frac{\alpha P_{fin}}{\lambda_{fin}A_{fin}}\right)^{0.5} h\right] + (n_{fin}-1)d\pi\delta_o\right\} \tag{3}$$

where the end of the fin is thermally insulated, Fig.1, i.e. $\left(dT_{fin}/dx\right)_{x=h} = 0$. According to equation (3), the convective surface of the flexible emitter consists of the total surface of the fins and the unfinned surface. The fins obtain various temperatures on their surface, so the heat exchanged with the airflow is corrected by the thermal fin efficiency, under the adopted conditions. Outlet air temperature in the case of a developed flexible finned surface, inside a circular channel of diameter *d*, Fig.1, can be determined using equation (4).

$$T_{a.out} = T_{a.in} + \frac{1}{\rho_a c_a V_a} q_{ref} \left\{ n_{fin} \left(\frac{P_{fin}\lambda_{fin}A_{fin}}{\alpha}\right)^{0.5} \cdot tanh\left[\left(\frac{\alpha P_{fin}}{\lambda_{fin}A_{fin}}\right)^{0.5} h\right] + \quad +\left(n_{fin}-1\right)d\pi\delta_o \right\} \tag{4}$$

should In this analysis, the attention is focused on the thermal irreversibility of the air, that is, the thermally generated entropy of the air due to its forced heating. The expression for the thermal entropy of air is represented by equation 5,

$$S_{air.\Delta T} = \rho_a \dot{V}_a c_a \int_{T_{a.in}}^{T_{a.out}} \frac{dT_a}{T_a} = \rho_a \dot{V}_a c_a ln\left(\frac{T_{a.out}}{T_{a.in}}\right) = \rho_a \frac{d^2\pi}{4} w_a c_a ln(\psi) \tag{5}$$

where $T_{a.in}$ and $T_{a.out}$ are the inlet and outlet air temperatures inside the flexible convective emitter, respectively. The entransy flow dissipation rate during the heating of air can be represented by the following expression.

$$E_{ent.in-out} = \rho_a \dot{V}_a c_a \int_{T_{a.in}}^{T_{a.out}} T_a dT_a = \rho_a \dot{V}_a c_a \left(T_{a.out}^2 - T_{a.in}^2\right) = \rho_a w_a c_a \frac{d^2\pi}{4} T_{a.in}^2 \left(\psi^2 - 1\right) \tag{6}$$

where the ratio of air temperature increase due to heating inside the flexible convective channel is denoted by $\psi = T_{a.out} / T_{a.in}$. Furthermore, the new irreversibility dimension ratio χ represents the ratio of the entransy flow dissipation rate and the thermal entropy of the air, [7] and [8], which is shown by equation 7.

$$\chi = \frac{E_{ent.in-out}}{S_{air.\Delta T}} = \frac{\left(T_{a.out}^2 - T_{a.in}^2\right)}{ln\left(\frac{T_{a.out}}{T_{a.in}}\right)} = T_{a.in}^2 \frac{(\psi-1)}{ln(\psi)} \tag{7}$$

Maximizing the irreversibility ratio χ implies minimizing the thermal entropy and maximizing the entransy dissipation ratio. However, obtaining minimum values of thermal entropy does not mean that these are at the same time optimal values of the process or geometric parameters of this heated system. The reason for the above is that entransy dissipation ratio and thermal entropy are not of a similar order of magnitude, so the maximum value of χ does not mean at the same time that its optimum has been obtained. Therefore, it is necessary to reduce both the entransy dissipation ratio and the thermal irreversibility ratio to a similar order of magnitude.

2.2. Novelty of Flexible Thermal Convective Emitter

This convective emitter is intended to forcedly but efficiently heat various fluids circulating thru a flexibly distensible conduit, consisting of an external and internal flexible housing.

A fluid flow is enabled by a pump, compressor, or fan. This device is mostly used by hydraulic and pneumatic plants. Because the internal heating housing is flexible and extensible, the control de/compressed air allows its length change according to the optimal process requirements for fluid heating. The conduit's length shall automatically be adapted, in the function of working parameters, temperature, and fluid flow rate. The primary advantage of this device represents the possibility of multiple changes in the optimal power of the electric heater and its convective surface. Thanks to this invention, a number of diverse devices with diverse dimensions and forms can be produced. Its installation and dissembling can be simply and quickly done, given that the electric current is used for fluid heating.

3. Results

In order to implement mathematical modeling, geometric and process parameters were established, which concretely define a flexible thermal convective emitter. The volumetric flow rate of air and the required heat flux from the inner surface of the flexible emitter to airflow were varied. The air flow through the convective emitter varied from 0.2m^{3}s^{-1} to 0.6m^{3}s^{-1}, at its constant inlet temperature of 20 ^{o}C. The flexible convective emitter is connected to an external electrical power of 220V. If the flexible convective emitter is in the zero position, then its length is a minimal value of 20cm. With an increase in input power, and in order to maintain a constant heat flux, its total convective surface instantly increases. With an increase in input power, while maintaining a constant heat flux, its total convective surface instantly increases. The increase in the convective surface is ensured by annular convective heat fins. As the input heat flux increases, the output air temperature also increases as expected, Fig.2a.

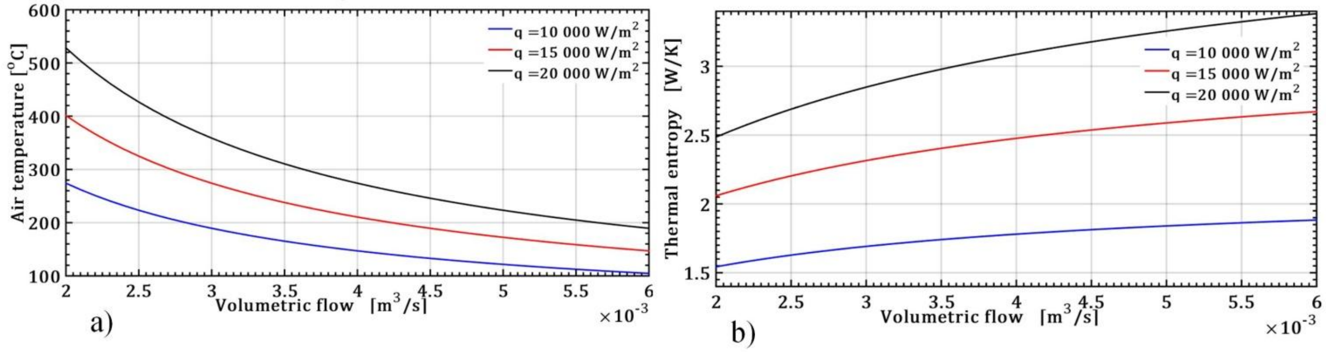

Fig. 2: a) Air temperature at the exit from the flexible emitter. b) Thermal entropy - during the convective transfer.

Smaller air flows have higher exit temperatures since it stays longer in the flexible duct. In this analysis, hydraulic irreversibilities are not included, but only thermal irreversibilities, through the mathematical model of thermal entropy, Fig. 2b.

Due to the heating of the air, its thermally generated entropy increases. Volumetric airflow, in addition, obtains a significant influence on thermal entropy, so that with its increase, thermal entropy also increases, even though the air temperature decreases. On the other hand, entransy flow dissipation rate decreases with increasing volumetric flow, Fig. 3a. Higher heat flux and air temperature have a higher entransy flow dissipation ratio. Comparing the values in Figs. 2b and 3a, entransy flow dissipation has large values compared to thermal entropy. The case is similar to the modification irreversibility ratio, Fig. 3b.

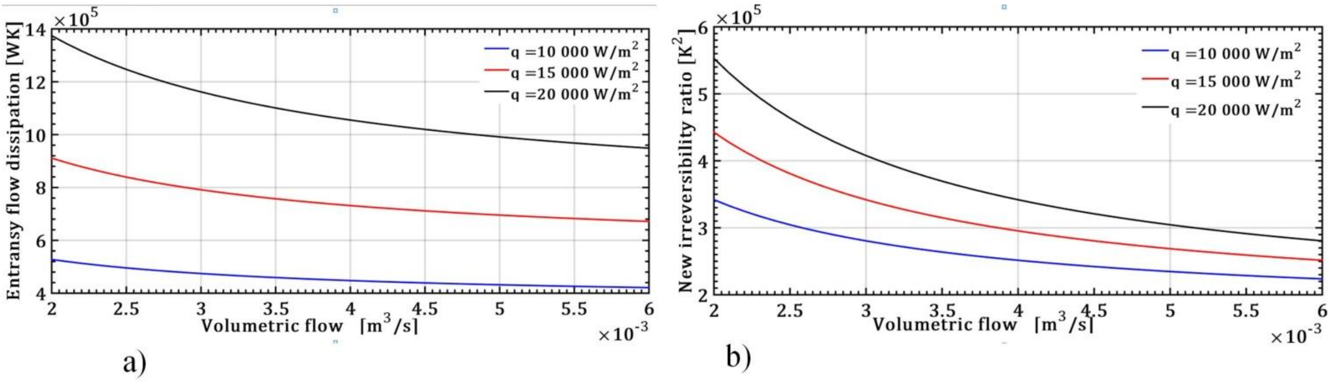

Fig. 3: a) Entransy flow dissipation - during air convective transfer through a flexible emitter.

b) Modification irreversibility dimension ratio.

Modification irreversibility dimension ratio χ represents the ratio of the entransy flow dissipation rate and thermal entropy, shown on Fig.3b. The values of this ratio are of the similar order of magnitude as the entransy dissipation ratio. The functional dependence of χ on the volumetric flow rate and heat flux in form is similar to the change in air temperature, shown in Fig. 2a.

The change in thermal entropy with the combined variation of the number of annular fins and the input heat flux is shown in Fig. 4. Thermal entropy increases with increasing volumetric airflow. The input heat flux obtains a significant role in the increase of thermal entropy, while the increase in the number of fins does not affect the values of thermal entropy. The opposite is the case with the entransy flow dissipation ratio, Fig. 5, where the smallest values are achieved at a minimum heat flux of $0.001 m^3 s^{-1}$. As the input heat flux increases, the entransy flow dissipation ratio increases linearly.

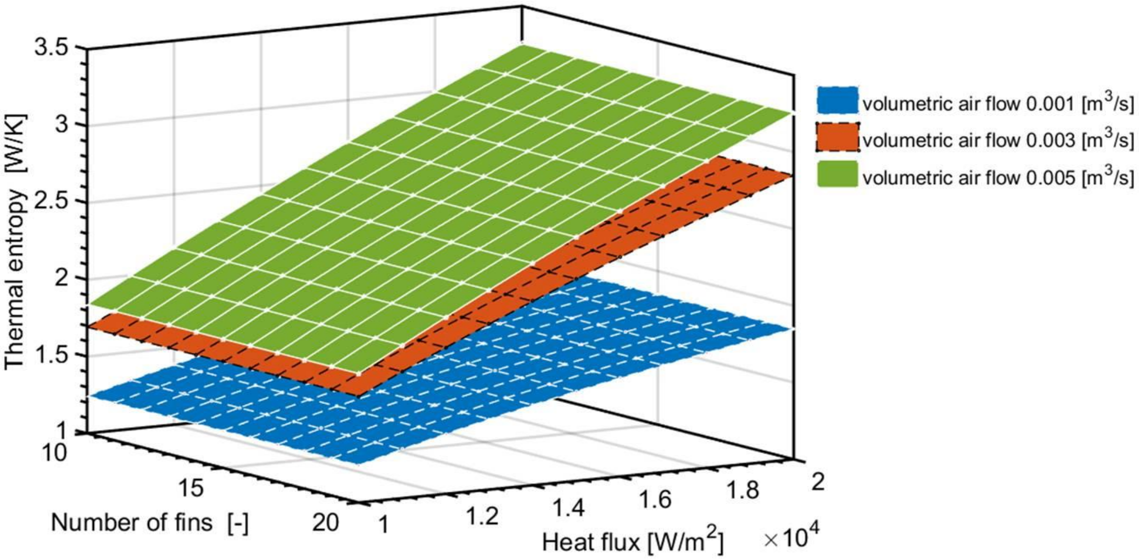

Fig. 4: Thermal entropy - variation heat flux and number of fins.

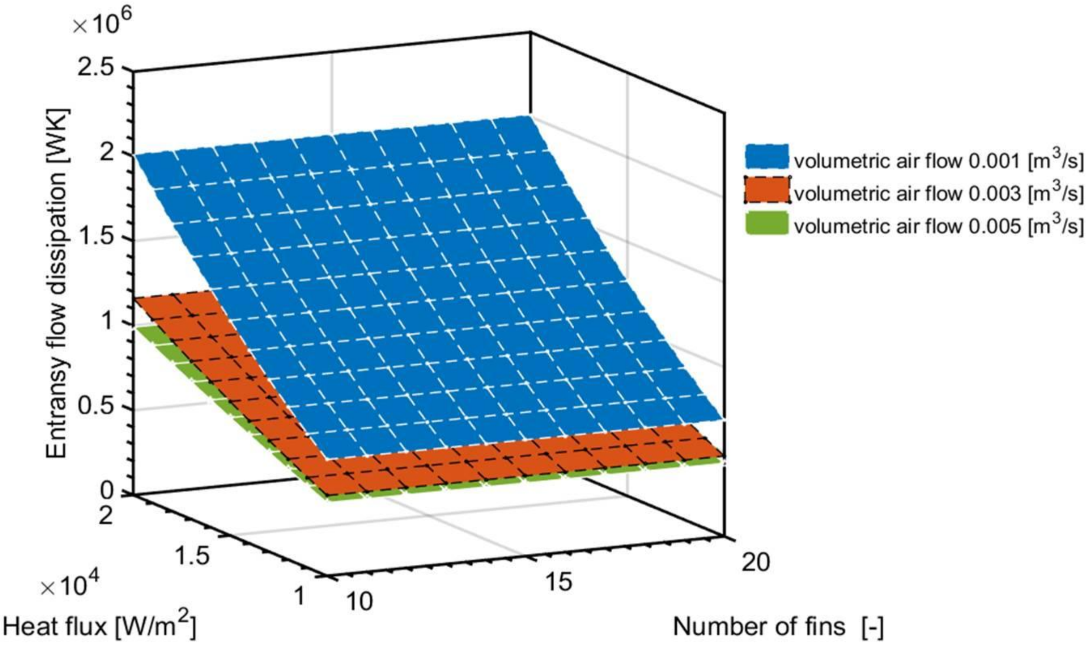

Fig. 5: Entransy flow dissipation – variation heat flux and number of fins.

4. Conclusion and Discussion

The flexible thermal convective emitter provides the possibility of an improved fluid heating solution by increasing the power of the electric heater while maintaining a constant value of the input heat flux. Existing electric heaters of this type contain limitations when increasing the input power of the heater at the same volumetric flow rate. As a consequence of the above, the convective surfaces of existing electric heaters are overheated, which reduces their service life. The adaptability of the synchronous change of the convective surface of the heater ensures that at the same fluid flow, the input power can be increased multiple times, which is not the case with existing convective heaters. A comparative analysis of thermal entropy and entransy dissipation ratio confirms the mutual character of these two physical quantities. While the thermal entropy increases with the air volumetric flow rate, the entransy dissipation ratio decreases. On the other hand, with the increase of the input heat flux, both of the mentioned physical quantities increase. The mentioned facts provide the possibility of maximizing the modified irreversibility distribution ratio, which is aimed at minimum entropy and maximum entransy flow dissipation ratio. The aforementioned limitation of this ratio can be eliminated by reducing the thermal entropy and entransy dissipation ratio to the similar order of magnitude.

5. Acknowledgements

This article is based upon work from the project Flexible Thermal Accumulation Convective Emitter, supported by the Ministry of Civil Affairs of Bosnia and Herzegovina.

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