

THE INFLUENCE OF AIR FLOW RATES AND ELECTRICAL CURRENTS ON HEAT TRANSFER THROUGH METAL FOAM POROUS MEDIA ⁺

دراسة تأثير معدلات جريان الهواء والتيارات الكهربائية على عملية انتقال الحرارة خلال وسط

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Abstract:

This study represents a model of radial heating element made from a combined of (Fe- Cr –Al) metals in porous, low density briquette foam in an air heater. The heating action occurred by converting the electrical energy into thermal energy and this is done by using electrical closed circuit includes the foam material as electrical resistance. The practical work includes a set of experiments using two types of metal foams different in porosities and same density. Experiments are conducted to evaluate the effects of air flow rates and electrical currents on the outlet temperature. The experimental results show significant changes in outlet temperature, and show reasonably good agreement with theoretical considerations.

Key words: Metal foam, porous media, electrical heater.

المستخلص:

هذه الدراسة تمثل نموذج من عنصر تسخين دائري مصنوع من المواد (Fe-Cr-Al) كوسط مسامي ذو كثافته واطئه كجزء من منظومه تسخين الهواء . فعل التسخين يحدث بتحويل الطاقة الكهربائيه الى طاقه حراريه وهذا يتم بتكوين دائره كهربائيه مغلقة يكون الوسط المسامي جزء منها كمقاومه كهربائيه. الجزء العملي من البحث يتضمن مجموعه من التجارب وذلك باستخدام نوعين من الوسط المعدني المختلف المساميه . التجارب اجريت لمعرفة تأثير مدى معين من معدلات جريان الهواء وكذلك مدى معين من التيارات الكهربائيه على درجة حرارة الهواء الخارج. النتائج العمليه اوجدت تغيرا مهما وملحوظا بدرجة حرارة الهواء الخارج واوجدت تطابقا جيدا مع الافكار النظرية التي اخذت

Introduction:

Air heating technology using heat generated by electrical current passed through a heating element is a widely used based on converting the electrical energy to thermal energy which is transferred to air flowing through the heating element. The phenomenon of internal heat generation is present in many situations, especially in the field of nuclear energy and composite superconductors [1]. Porous materials have been studied for many years for application in heat transfer [2]. Potential applications of this heating method include the household and office space heater and particulate filtration for diesel engine exhaust after

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treatment. [3].

The use of open-cell foams have been widely increasing given by its diverse properties in various areas including aerospace, electronics and automotive among others [4, 5, 6]. They are a relative new class of materials with very promising applications in which its low density and other thermal, mechanical and electrical properties make this material an excellent means of performance improvement.

Among their, current applications, open cell metal foams are found useful for the construction of light weight structures, energy adsorption devices, currently being used by some vehicle manufactures, and for various fluid flow and thermal applications which is our interest in this paper.

Although its proven to be very promising, the use of open cell metal foams in fluid flow and heat transfer application requires an extensive effort to better understand the behavior of the fluid flowing through its matrix composition and the heat mechanism occurring in the medium.

Foams are the result of a two phase combination created by various processes, most of which include the dispersion of a gas through a liquid without dissolving the gas completely. This is very similar to the emulsion process (combination of two immiscible liquids) but having the difference that a gas phase must exist in the foam.

As we know, we have two types of cell metal foams are found open-cell and close-cell, the difference between them are mainly how the geometry of the cell is formed. In the open cell group, the cells are not closed from each other and the of other materials through one cell occurs freely to another adjacent. The type of foam is generally created during the foam manufacturing by removing the inter-cellular membranes of closed cell foam [4].

In the closed cell arrangement the surface tension and wetness scales increase and the geometry takes a very different shape compared to the open cell arrangements. It is characterized by the continuous cell walls which completely close the cells from one another with formation of individual cell compartments. The cells nearly take a spherical shape in these of metal foams. It is designated as wet foam when the liquid fraction exceeds 5%

The main characteristic of open metal foam is the pore size and relative density. The experimental work in this paper will focus on the fluid flow behavior and heat transfer. Metal foam is composed of a porous matrix that consists of tortuous, irregular shaped flow passages. Heat transfer takes place between the surface of solid matrix and fluid.

The material commonly used to be as a heating element must has a high resistance with electrically conductive, in addition to be chemically stable to both oxidation and corrosion at high temperature and has a high melting point, such metals are (Fe-Cr-Al), (Ni-Cr), Cermets (MoSi_2), Carbon compounds, Silicon carbide (SiC), Tungsten, Molybdenum and Platinum.[7]. In this study the (Fe-Cr-Al) alloy is used as a metal foam heating element. This study investigates the use of porous metal foam as the electrical resistance heating element.

To produce the selected alloy the slurry of metals powder with kelzan binder was coated to the polyurethane foam and fired in a vacuum furnace. In this case the polyurethane foam was burned out during firing leaving the hollow hole inside each of the ligaments. The bulk (Fe – Cr – Al) alloy has an electrical resistivity of about ($1.4\mu\Omega\text{m}$) [8]. In comparison the copper and (316) stainless steel have electrical resistivity of (0.017 to $0.74\mu\Omega\text{m}$) respectively. Since the metal foam is made of sintered powder, as well as highly porous, its electrical resistivity is much higher and will vary with density.

There are various manufacturers to supply metal foams among them are ERG, Cymat, Recemat, Porvair (USA) and even Mitsubishi Materials (Japan).

Theoretical considerations:

In order to evaluate the total heat generated in the disc, assume a selected element of (dr) from the foam, as shown in fig. (1). the inner radius (r_i) from the centre of the rod, and (r_o) is the outer radius of the element, the electrical resistance in the radial direction of the ring cross section with distance from the centre is:

The metal foam disk is assumed to consist of a series of ring segments, as shown in Fig1. Each ring segment has the inside and outside radius of r_i and r_o , respectively, and
 $dr = r_o - r_i$

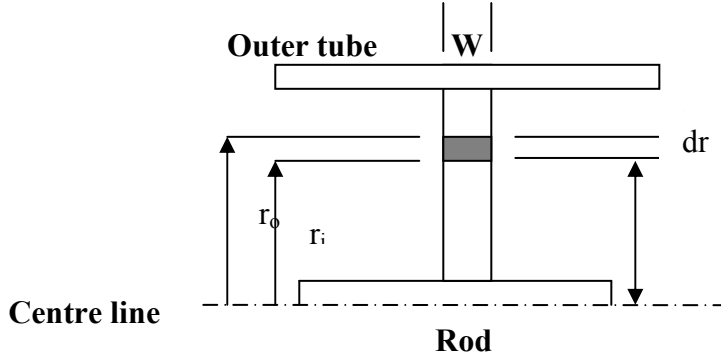


Fig. (1): A selected element from foam metal disc.

In the metal foam disk, the electrical resistance in the radial direction of a ring cross-section with distance r from the center is designated as R . For an infinitesimal circumferential element

$$R_{ele} = \rho \frac{dr}{A} \quad (1)$$

Where

ρ = electrical resistivity of the metal foam

A = is the circumferential area of the ring cross-section

$$A = 2\pi r W \quad (2)$$

Integrating for a ring of finite thickness from r_i to r_o , the inner and outer radii of the ring respectively, the electrical resistance of the ring R_{ring} is derived as follows:

$$R_{ring} = \int_{r_i}^{r_o} \rho \frac{dr}{2\pi r W} = \frac{\rho}{2\pi W} \ln \left(\frac{r_o}{r_i} \right) \quad (3)$$

Since the ring segment is usually very thin, the area A of ring can be approximated by $\pi(r_o + r_i)w$ and the R_{ring} can be expressed as:

$$R_{ring} = \int_{r_i}^{r_o} \rho \frac{dr}{\pi W (r_o + r_i)} = \frac{\rho (r_o - r_i)}{\pi W (r_o + r_i)} \quad (4)$$

The total electrical resistance of the disk, R_{disk} , is simply the sum of the resistances of each ring

$$R_{disc} = \sum R_{ring} \quad (5)$$

The total heat generated in the ring by electric resistance heating, Q_{ring} , is calculated by

$$Q_{disc} = I^2 R_{disc} \quad (6)$$

Part of the heat generated is lost through the insulation to the ambient environment. For cylindrical 1-D conduction, this heat loss, Q_{loss} , is given by [9]

$$Q_{loss} = \frac{2\pi (T_b - T_\infty) KL}{Ln\{(r_{ins} + t_{ins})/r_{ins}\} + l/h_o} \quad (7)$$

where T_b is the temperature of the tube, T_∞ is the ambient temperature, k is the thermal conductivity of the insulation, l is the length of the cylinder, r_{ins} is the inner radius of the insulation, and t_{ins} is the thickness of the insulation, h_o is the heat transfer coefficient of outside air. The tube has a thin wall relative to the inside diameter and is made of highly thermal conductive material. In the cross-section perpendicular to the tube center axis, temperatures at inside and outside diameters of the tube are assumed to be the same. The bulk temperature increase, ΔT , in the airflow across the metal foam heating element can be estimated by

$$\Delta T = \frac{Q_{disc} - Q_{loss}}{m C_p} \quad (8)$$

Where m is the mass flow rate and C_p is the specific heat of the air.

If assuming a perfect insulation, then there is no heat loss to the ambient air and Q_{loss} in equation (8) can be canceled.

1 Application of the Analytical Model

An example is given here of a Fe-Cr-Al foam disk of $w = 13$ mm, inner diameter $d = 6.35$ mm to fit the inner rod and outside diameter $D = 50.8$ mm to fit inside a tube. The measured electrical resistivity of 10 wt%, 90 ppi foam is $99.6 \mu\Omega\text{m}$.

For an electrical current $i = 40$ A, about 6.23 W of heat is generated in the disk Fe-Cr-Al metal foam element

2.1.1. Analytic Results Assuming Zero Heat Loss ($Q_{loss}=0$)

Using material properties of inlet air at atmospheric pressure, a temperature of 27°C , and an air flow rate of 5 L/min, results in an m of 7.74×10^{-5} kg/s, and C_p of 1007 J/kgK [9]. Assuming the previously determined heat generation of 6.23 W, and an adiabatic boundary condition on the outer tube surface, i.e., $Q_{loss} = 0$, temperature rise of the air, ΔT , is 79.9°C based on Eq. (8). The outlet temperature therefore, is predicted to be 107°C . This temperature rise represents an ideal case in which all electrically generated heat is carried away by the air without any loss, i.e., the outer tube is adiabatic and no heat transfer to the inner rod.

Experimental Work

Experimental work can be divided into three divisions as follows

1. Design of metal foam heater
2. Setting up the system
3. Carrying up the experiments

The system used in this study (which was set up in I.A.E.C) is showed in fig. (3), and the diagram in fig. (2) shows the heating element part in that system which includes a metal foam disc installed vertically inside a copper tube and a cylindrical copper rod passed through the

centre of the metal foam which is connected to the positive end of DC power supply, wherein the negative end is connected to the outside tube. The electrical current flows from the centre rod to the tube through the metal foam. The high electrical resistance of metal foam generates heat which is practically transmitted to the air which is flows through the metal foam. Temperature of the air before and after passing the heating element are measured by using thermocouples type K Eliweli Mode EW-282A- , one of these thermocouples measures the inlet air temperature and another two measure the outlet temperatures installed in a certain distances from the foam disc. All these three thermocouples are placed close to the centre line of the tube. The outside surface of the tube is a thermal insulated by a glass wall in order to decrease or minimize the heat losing.

According to this circuit the electrical resistance generates heat which is transmitted by the air flowing through the metal foam using a flow meter type Brooks instrument 5850 Elliot. The mass flow controller consists of two parts, a display unit and a control valve. The control valve is connected to the compressed air supply in the building by a pressure regulator, to reduce the effects of pressure variations in the line. A differential pressure gage was connected between the inlet and atmospheric conditions in an effort to compare pressure drop through the heater at the different flow rates and foam parameters.

Even with a very sensitive 0-2 inH₂O gage, no measurable pressure drop occurred. This is probably because the flow rates studied in these experiments were quite low and the heating element was thin 24 in the axial direction. In this experimental work the samples used were manufactured by ERG Corporation in USA.

The foam metal used here has two pore sizes with one weight density. The two pore sizes are 70 and 90 ppi (pores per inch) which correspond to about (0.4-0.6) and (0.3-0.5) mm respectively. The selected alloy density is (10 wt %) relative to the density of a solid Fe-Cr-Al alloy.

. The ambient room temperature also measured using a thermocouple located outside the system.

Two sets of experiment were conducted. One is a (5 hr) long duration test using (10%wt, 90ppi) metal foam heater to study its characteristics for an extended period of time and to evaluate the time required to reach the steady-state heating condition. Another is a set of tests conducted on the two metal foam heaters. For each metal foam heater, several levels of air flow rate at (0.5 to 5.0) L/min. and three levels of electrical current (20, 30, and 40) Amp were tested.

The ambient, inlet, and averaged outlet temperatures were recorded during the long-duration test. During the short duration tests, a single inlet thermocouple is used.

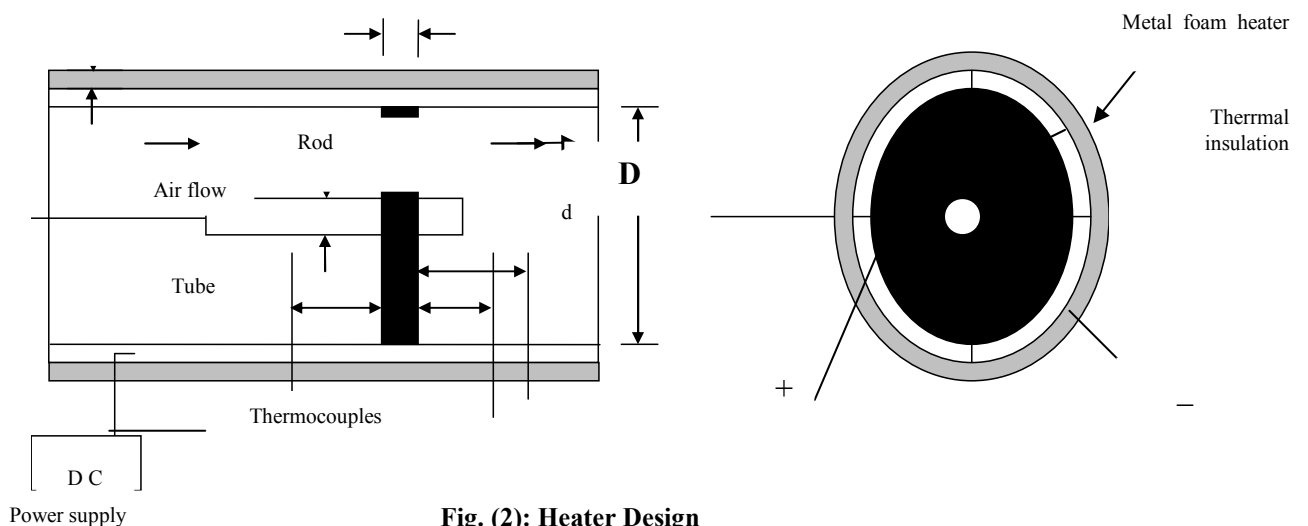
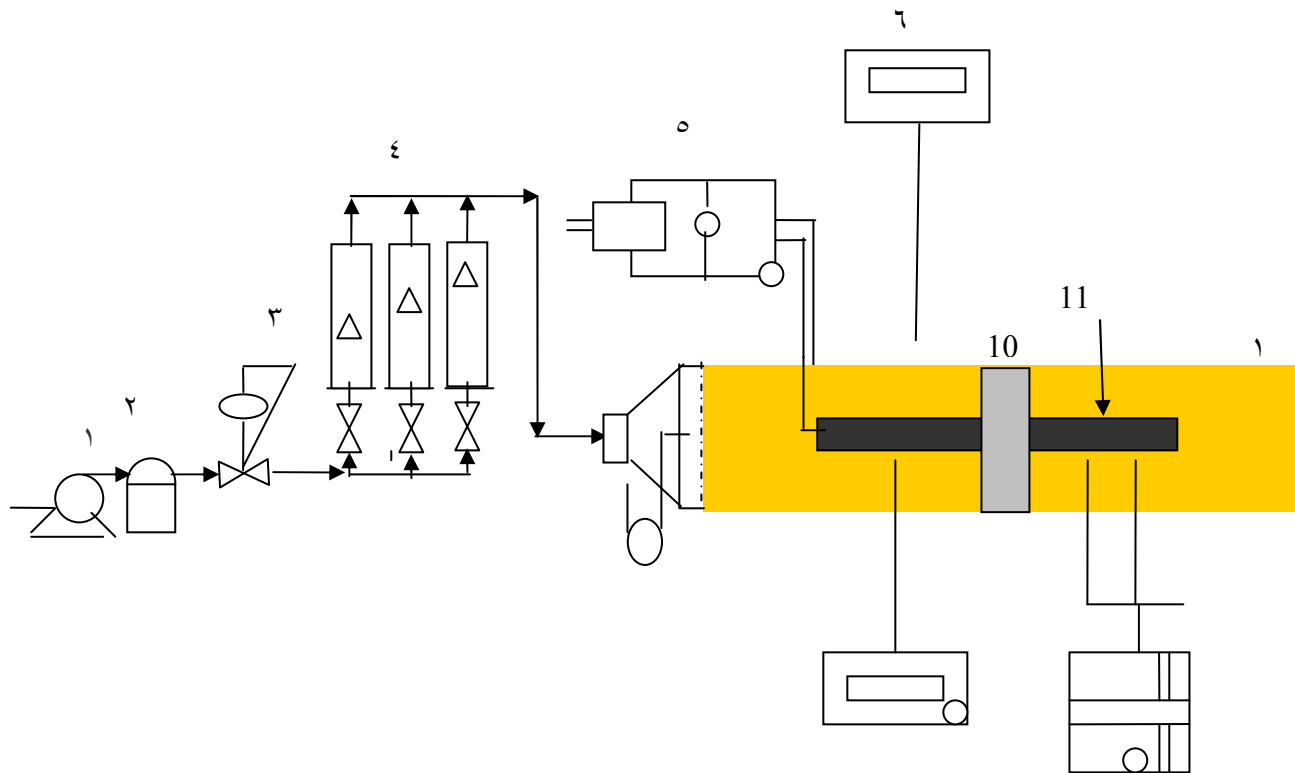


Fig. (2): Heater Design



- | | |
|----------------------------|---------------------------------|
| 1. Gas Compressor | 7. Manometer |
| 2. Damping Tank | 8. Digital Thermocouple |
| 3. Filter- regulator Valve | 9. Digital Time- Temp. Recorder |
| 4. Flow meters | 10. Metal-Foam Porous – Media |
| 5. Electrical Circuit | 11. Copper Rod |
| 6. Digital Thermometer | 12. Copper Tube |
| | 13. Air Distributor |

Fig (3):Experimental Setup

Experimental results:

1 Steady –state temperatures of a foam heater:

Figure [4] shows the inlet, ambient, and averaged outlet air temperatures recorded for the (5 hour) test. The ambient temperature starts at about (32 c°) and gradually drops to (29 °)after (5 hr). All the tests were conducted in a shop floor without temperature control, which is the reason for this temperature fluctuation

The inlet temperature, (T_i), gradually increased from the ambient (32 c°) to about (47 c°) after (3 hr) of testing. The gradual increase in (T_i) due to the heat conducted from the outer tube and inner rod to the front end of the heating device that pre-heats the inlet air. Following the trend of ambient temperature, (T_i) (slightly dropped by about (2 c°) from hour three to five

The average outlet temperature, t_o , also gradually increased to about (64 c°) after 3 hours. The difference of outlet and inlet temperature is also in figure above.

The temperature rise reaches the steady- state condition of about (16 c°) after about (20 min.).

2 Effects of air flow rate and electric current:

Results of the temperature rise ($T_o - T_{\infty}$) of the (30) test, conditions using (2) metal foam heating elements at (5) levels of air flow rate and (3) levels of electrical current flow after (20 min.) of heating are shown in Figures (5&6). The (20 min.) is selected based on the results in Figure (4). The temperature rise, ($T_o - T_{\infty}$), is near the steady- state after (20 min.)

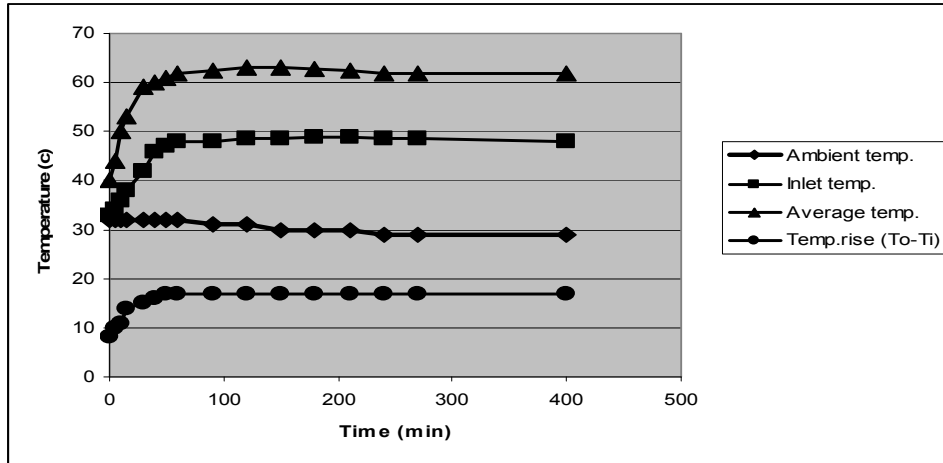


Fig. (4): Variation of various temperatures versus time

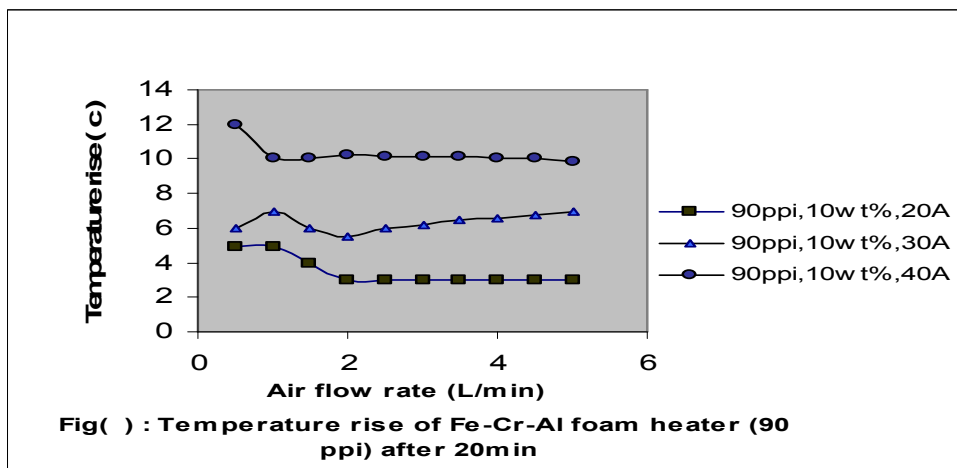


Fig () : Temperature rise of Fe-Cr-Al foam heater (90 ppi) after 20min

Fig. (5): Effect of air flow rate on Temp. rise using 90 ppi metal foam

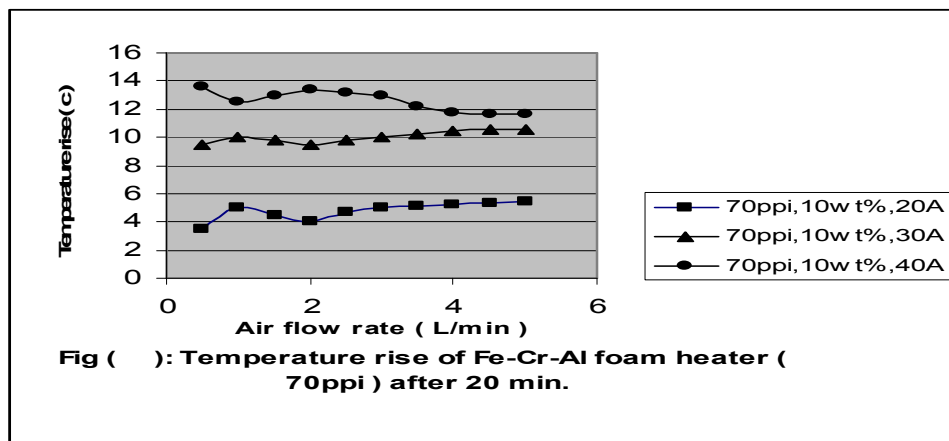


Fig () : Temperature rise of Fe-Cr-Al foam heater (70ppi) after 20 min.

Fig. (6): Effect of air flow rate on Temp. rise using 70 ppi metal foam

Discussion:

The effect of electrical current on outlet temperature is as expected: "When more electrical current is supplied to the metal foam heater, more heat is generated, and the temperature rise is greater."

The effect of the air flow rate on temperature rise is not as obvious. As the air flow rate increases, the residence time of the air through the heater is likewise decreased, which would lead to lower outlet temperatures.

At the same time, however, the convective heat transfer coefficient increases, this would lead to more heat gain and higher temperatures (7, 8). Balance of the short residence time and high thermal convection can be seen in the mixed temperature rise results in Fig. (6). The porosity of the metal foam changes the electrical resistivity and the temperature rise, for (10 wt%) Fe-Cr-Al metal foam, the (70 ppi) porosity metal foam has higher electrical resistance (Fig.6) , which results in the greater temperature rise than the (90 ppi)heater under the same testing condition.(Fig. 5)

Compared to the analytical model prediction of (40 c°)temperature rise, the experimental measurement of the steady- state temperature rise for the same (10wt%, 90 ppi) metal foam heater show about (33 c°), which is reasonably good agreement considering the complicated nature of the system. Compared to the analytical modeling with adiabatic boundary condition on the tube, the (80 c°) temperature rise is much higher than the experimental measurement. This indicates that a significant portion of the heat is loss through the tube to the surroundings.

Conclusions:

In this study a novel metal foam heater is studied; Two prototype metal foam heaters made of (70 and 90 ppi) Fe-Cr-Al foam at (10 wt %) were produced.

Temperature rise of a metal foam heater for an extended period of time of heating test is studied to under stand the time required to reach the steady state heat transfer condition.

Experiments were conducted using the two heaters at five levels of airflow rate and three levels of electrical current to investigate the temperature rise of the airflow through the metal foam heater showed reasonably good agreement with experiment of measurement of the steady- state temperature rise in the (90 ppi 10 wt %) metal foam heater under (40 A) electrical current and (5 L/min.) airflow rate.

It is possible to increase the resistance of the heating element by reducing the width of the metal foam and raise the temperature of the metal foam. However, under a constant flow rate, residence time of the air in the foam is shortened. This could possibly reduce the heat transferred to the air. If thickness is created. decreased with increasing radius, more uniform heat generation rate can be created.

Nomenclature:

A	cross section of ring element. [mm]
c_p	specific heat of the air [j /kg.k] C
h_o	heat transfer coefficient [w/m ² .k]
I	electrical current. [Amp]
K	thermal conductivity of the insulation. [w/m ² .k]
L	length of the cylinder. [mm]
M	the mass flow rate. [kg/s]

Q_{disc} total heat generated in the disc by electric resistance [watt]
 r_{ins} the inner radius of insulation [mm]
 R_{disc} electrical resistance of the disc [$\mu\Omega m$]
 R_{ring} electrical resistant of ring element. [$\mu\Omega m$]
 R_{ele} electrical resistance. [$\mu\Omega m$]
 T_b temperature of the tube [$^{\circ}C$]
 T_{∞} ambient temperature. [$^{\circ}C$]
 T_i inlet air temperature before foam. [$^{\circ}C$]
 T_o out let average air temperature after foam. [$^{\circ}C$]
 t_{ins} thickness of the insulation. [mm]
 ΔT bulk temperature. [$^{\circ}C$]
 w width of element. [mm]
 ρ electrical resistivity of the metal foam. [$\mu\Omega m$]

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