World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:15, No:5, 2021

Numerical and Experimental Study of Heat Transfer Enhancement with Metal Foams and Ultrasounds

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Abstract**—**The aim of this experimental and numerical study is to analyze the effects of acoustic streaming generated by 40 kHz ultrasonic waves on heat transfer in forced convection, with and without 40 PPI aluminum metal foam. Preliminary dynamic and thermal studies were done with COMSOL Multiphase, to see heat transfer enhancement degree by inserting a 40PPI metal foam (10 × 2 × 3 cm) on a heat sink, after having determined experimentally its permeability and Forchheimer's coefficient. The results obtained numerically are in accordance with those obtained experimentally, with an enhancement factor of 205% for a velocity of 0.4 m/s compared to an empty channel. The influence of 40 kHz ultrasound on heat transfer was also tested with and without metallic foam. Results show a remarkable increase in Nusselt number in an empty channel with an enhancement factor of 37,5%, while no influence of ultrasound on heat transfer in metal foam presence.

Keywords**—**Enhancing heat transfer, metal foam, ultrasound, acoustic streaming, laminar flow.

NOMENCLATURE

F:	volume force, ($N.m^{-3}$)
ρ:	density, ($Kg.m^{-3}$)
P:	pressure, (Pa)
υ, u :	velocities ($m.s^{-1}$)
μ, μ':	dynamic viscosity (Pa.s)
f :	Forchheimer's coefficient
L:	length (m)
ΔP:	pressure drop (Pa)
K:	permeability (m^2)
Q_m:	mass source or sink (kg)
Q:	heat flow (W)
ε:	porosity
k_{eff} :	effective thermal conductivity (W/m.k)
η_{MF}:	metal foam enhancement factor
η_{us} :	ultrasonic enhancement factor
$\overline{Nu}$:	average Nusselt number
Nu_x :	local Nusselt number

I. INTRODUCTION

A. Acoustic Streaming

THE concept of acoustic streaming is a term designating a phenomenon of rotational movement of fluid under an acoustic wave action; we can define three types, based on criteria related to appearance mechanisms and length scales, on which the movement of fluid is propagated. The first one describes a global macroscopic flow, resulting from spatial attenuation of an acoustic wave, called Eckart current [1]; a second type can develop if the wave propagation regime is stationary, in which case the acoustic streaming is directly driven by dissipation phenomenon in an acoustic boundary layer [2]. The last type describes micro-convection phenomena appearing around an oscillating surface in a fluid. The heat transfer by natural convection in presence of stationary and progressive ultrasonic waves generated by a vibrating aluminum bar placed on two Langevin-type transducers is studied experimentally by [3]. This indicates that acoustic streaming is the dominant factor in convective heat transfer. However, the standing wave creates a greater temperature drop than the progressive wave for a given power supply. The acoustic streaming induced by ultrasonic vibrations associated to convection enhancements is studied by [4]. The acoustic streaming model and streaming velocity are observed experimentally. Reference [5] experimentally studied the acoustic streaming induced by a piezoelectric transducer in an open channel. A stationary rotational flow was observed by particle imaging velocimetry (PIV). The maximum velocity of acoustic streaming is about 0.16 cm/s with a frequency of 30 kHz. A numerical analysis added by the same authors in 2007 [6] reveals that the maximum heat transfer is obtained for a multiple air gap of one or half wavelength.

Few articles study the heat transfer enhancement in forced convection. The main experimental installations use the geometry of shell-and-tube heat exchangers using high viscosity coolant fluids (water), in order to favor the appearance of acoustic cavitation, which is the phenomenon that causes turbulence in the fluid [7]-[10].

B. Metallic Foam

Many recent works are done about the heat transfer intensification by metal foam. In 2013 [11] carried out an experimental study in forced convection in presence of two different foams, aluminum and copper; the goal of this study is to see the influence of thickness and thermal conductivity of metallic foams on heat transfer and pressure drop in a vertical channel. Another experimental study is done by [12] in 2015 to clearly determine the relationship between convection and conduction of fluid through a metallic foam. In 2016 [13] studied experimentally the effect of flow velocity, height and metal foam samples' arrangement both on pressure drop and heat transfer in a rectangular channel. Results showed a heat transfer enhancement with metallic foam compared to an empty channel for the same ventilation power, and that increasing

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foam sizes accentuates turbulent kinetic energy, which improves heat exchange.

As mentioned above, most studies on heat transfer enhancement with ultrasound in forced convection use a liquid as coolant in shell-and-tube heat exchanger configurations. But in electronic field, components have the advantage of being more performant since they are increasingly cooled, and air is the ideal fluid for direct contact cooling. And as the viscosity of air is very low, making it an ideal fluid in the presence of metal foams to minimize pressure drop. For this purpose, we are going to carry out an experimental study on the enhancement of heat transfer with ultrasound and metal foam in forced convection using air as heat transfer fluid.

II. Theory

A. Acoustic Streaming

According to linear acoustics, when a sound wave propagates through a medium, the medium itself does not move with the wave but oscillates, this oscillation transmits acoustic energy. However, when a high intensity sound wave propagates, the wave is governed by non-linear acoustics and is attenuated by viscosity effect and inertia of propagating medium, which leads to a pressure gradient along the direction of wave propagation. Resulting phenomenon is the acoustic streaming, [14] explained acoustic streaming theoretically as:

$$F = \rho\vartheta\left(\frac{\delta\vartheta}{\delta t} + (\vartheta.\nabla\vartheta)\right) = -\nabla P + \left[\mu' + \left(\frac{4}{3}\right)\mu\right]\nabla\nabla\vartheta - \mu\nabla\times\nabla\times \quad (1)$$

We can write P, ρ and υ as a sum of the increasing and decreasing terms of parameters,

$$P = P_0 + P_1 + P_2 + \cdots$$
$$\rho = \rho_0 + \rho_1 + \rho_2 + \cdots$$
$$\vartheta = \vartheta_1 + \vartheta_2 + \cdots$$

Index (0) represents static conditions, index (1) represents first-order conditions, index (2) represents second-order conditions etc... The first-order terms P_1, ρ_1 and $\vartheta_1$are obtained from linearization of Navier-Stoke equations with a temporary impedance equal to $(e^{j\omega t})$, with $j = \sqrt{-1}$, ω is the excitation frequency and t represents time. Because of the non-linear interaction with sound wave, this harmonically varying first order motion creates a second order term composed of a second harmonic frequency term and a zero-frequency term, this zero-frequency term represents a constant fluid flow. Time-averaged volume force at the origin of constant flow is estimated from a first-order velocity field as follows:

$$F = -\rho_0\langle(\vartheta_1.\nabla)\vartheta_1 + \vartheta_1(\nabla\vartheta_1)\rangle \quad (2)$$

where $\langle X\rangle$ means "average time" of X. Volume force in (2) varies as square of first-order velocity and square of second-order velocity which is calculated from:

$$\mu\nabla^2\vartheta_2 - \nabla P_2 + F = 0 \quad (3)$$

The second order velocity v_2 represents acoustic streaming velocity and causes a circular air flow near an object in presence of a high intensity sound field [15].

B. Metallic foam

Dependent variables in Brinkman equation are Darcy's velocity and pressure. Flow in porous media is governed by a combination of continuity and motion equations, which together form the Brinkman equations:

$$\frac{\partial}{\partial t}(\varepsilon_p\rho) + \nabla(\rho u) = Q_m \quad (4)$$

$$\frac{\rho}{\varepsilon_p}\left(\frac{\partial u}{\partial t} + (u.\nabla)\frac{u}{\varepsilon_p}\right) = -\nabla P + \left[\frac{1}{\varepsilon_p}\left\{\mu(\nabla u + (\nabla u)^T)\frac{2}{3}\mu(\nabla.u)I\right\}\right] - \left(K^{-1}u + \frac{Q_m}{\varepsilon_p^2}\right)u + F \quad (5)$$

Forchheimer corrects Darcy's law for high fluid flow rates by adding a viscous force proportional to flow velocity square:

$$F = -\rho\beta|u|u$$

with

$$\beta = \frac{f}{\sqrt{K}}$$

For heat transfer modeling in a porous media, we use the energy equation by introducing the effective solid-fluid values:

$$(\rho C_p)_{eff}\frac{\partial T}{\partial T} + \rho C_p u.\nabla T + \nabla q = Q \quad (6)$$

$$q = -k_{eff}\nabla T$$
$$k_{eff} = \varepsilon_p k_p + (1 - \varepsilon_p)k$$

- Local Nusselt Number

$$\mathrm{Nu_x} = \frac{\mathrm{h_x D_h}}{k_\mathrm{f}} \quad (7)$$

- Average Nusselt number

$$\overline{Nu} = \frac{1}{L}\sum_{i=1}^{i=n}\mathrm{Nu_{xi}}.\Delta xi \quad (8)$$

- Enhancement factor
  - By Metal Foam

$$\eta_{\mathrm{MF}} = \frac{\overline{Nu}_{MM} - \overline{Nu}_{Canal\,vide}}{\overline{Nu}_{Canal\,vide}}$$

  - By Ultrasound

$$\eta_{\mathrm{us}} = \frac{\overline{Nu}_{US} - \overline{Nu}_{sans\,US}}{\overline{Nu}_{sans\,US}}$$

III. Experimental Set-Up

The aim of this work is to study the influence of ultrasounds on heat transfer in forced convection, with and without metallic foam exposed to an air flow.

Method adopted in our work consists in observing temperature evolution of heat sink, on which is placed a metallic aluminum foam sample with a pore density of 40PPI exposed to ultrasound at a frequency of 40 kHz. A test bench was designed and realized at LTMP laboratory of USTHB for a simultaneous dynamic and thermal study. Instrumentation used in this study is shown in Fig 1. It is a mini wind tunnel that allows the study of forced convection flows in single-phase regime. It consists of a convergent inlet section connected to a horizontal primary channel; a type K thermocouple is placed at the convergent section to measure air temperature at channel inlet. To measure air velocity in primary channel, a hot-wire air velocity transmitter of HDUV3TS series is used. Secondary channel downstream of test section conveys hot air to the outside in an even manner by means of a single-phase centrifugal fan. The fan is controlled by a Schneider Electric frequency meter (Altivar ATV312HU22M2) which varies air velocity at the inlet of the primary channel by varying output frequency between 0 and 50 Hz.

Test section consists of a thermal part and an ultrasonic part. Thermal part consists of a heat sink where type K thermocouples are inserted in order to measure its wall temperature.

Ultrasonic part is composed of two piezoelectric transducers with a frequency of 40 kHz, placed on a thin aluminum plate in direct contact with air passing through the test vein. The different configurations studied are illustrated in Fig. 2.

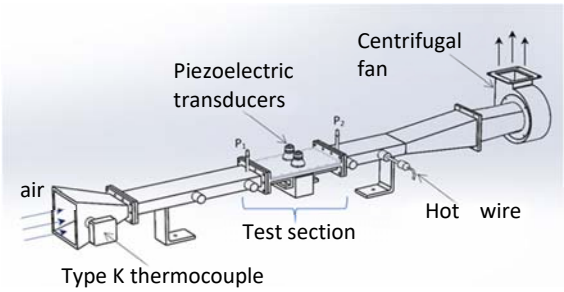
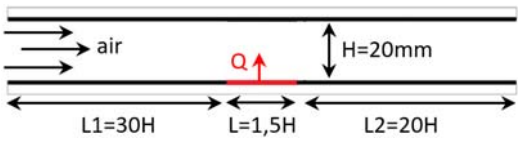
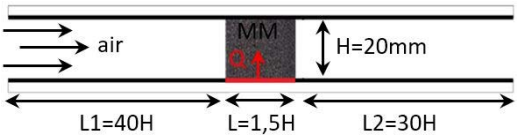


Fig. 1 Schematic diagram of test bench



(a)



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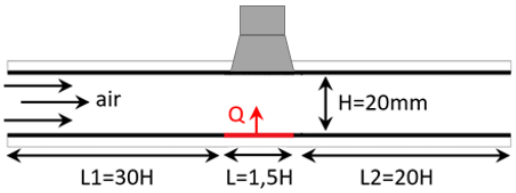

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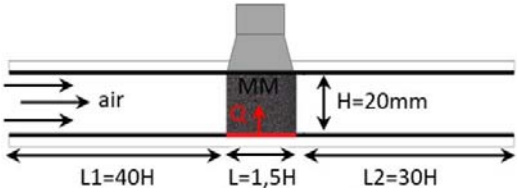

(d)

Fig. 2 Various configurations studied; (a) Configuration I (empty channel without US); (b) Configuration II (channel with MF without US); (c) Configuration III (empty channel with US); (d) Configuration IV (channel with MF and US)

IV. Results

The aim of this part is the presentation and exploitation of different results obtained numerically and experimentally. The method presented is based on the observation of temporary evolution of parietal temperature provided by instrumentation set up, which allows the calculation of energy balances in order to quantify the degree of improvement either by MF or by US. Several temperature and velocity profiles are plotted for a given configuration.

The temperature measurements in test section are acquired in two phases. After thermal stabilization, a first phase of temperature measurement is carried out without ultrasound (configuration I and II). Arithmetic average is then calculated for each of temperatures measured to obtain average heat exchange coefficient and then Nusselt number in silent regime. After starting up ultrasound (configuration III and IV), a new period of system thermal stabilization is required, after which the procedure of phase 1 is repeated in order to obtain the heat exchange coefficient in acoustic regime.

Configuration I was used as a reference to quantify heat transfer enhancement degree by insertion of a metal foam subjected to the effect of a 40 kHz frequency acoustic streaming.

Fig. 3 shows the velocity profile upstream of test section at a distance from the channel entrance of 5H, which corresponds to a parabolic profile, so that temperature measurements are made under dynamic establishment conditions. Fig. 4 shows variation of wall temperature measured in middle of heat sink parallel to flow. We notice an increase in temperature which is explained by the appearing of a thermal boundary layer. And the lower the temperature gradient between the wall and the fluid, the greater the boundary layer thickness, so heat exchange coefficient decreases as we move away from the leading edge of heat sink.

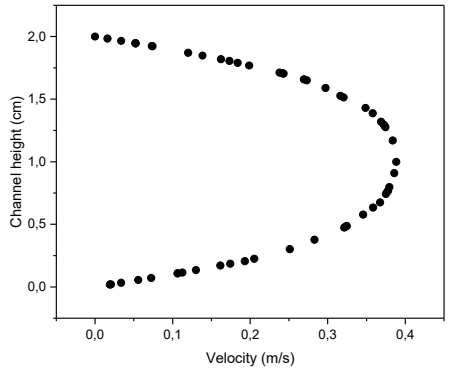

Fig. 1 Velocity profile in an empty rectangular channel (10 × 2 cm) upstream of the test section for a maximum velocity of 0.4 m/s

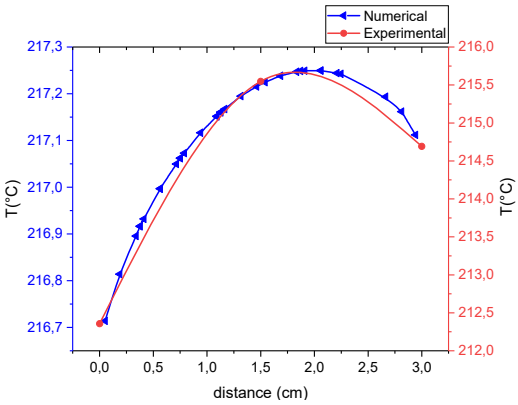

Fig. 4 Variation of wall temperature in middle of heat sink for a flow velocity of 0.4 m/s and a heating power of 50W.T_{input} = 20 °C

Fig. 5 shows the temperature variation on the surface of heat sink. It can be seen that the temperature decreases away from plate center because the walls of test section are exposed to outside temperature condition of 20 °C.

Configuration II (channel with MF) aims to study the influence of metallic foam on heat transfer. Metal foam is placed on heat sink by applying a thermal paste to minimize contact resistance, and it occupies the entire height of channel which will ensure that air flow passes entirely through its pores. Darcy-Forchheimer's law corrects Darcy's law for high fluid flow rates in porous media by considering inertial effects.

A slightly changed form of Forchheimer equation can be obtained by dividing both sides of equation by average velocity u .

$$\frac{\Delta P}{Lu} = \frac{\mu}{K} + \frac{\rho f}{\sqrt{K}} u \qquad (9)$$

By plotting pressure drop (ΔP/Lu) as a function of flow velocity Fig. 6, permeability and Forchheimer's coefficient of metal foam used in this experiment can be determined by analogy with trend curve equation shown on the graph. Results are shown in Table I.

Fig. 7 shows axial velocity profile inside the metal foam for a Da = 6.22510-3. A thin boundary layer appears on the wall. However, an increasing Darcy number increases the permeability within the channel, leading to a non-linear velocity distribution. Flatness of velocity profile decreases as Darcy number increases. When Da tends to infinity, velocity profile approaches a shape similar to that observed in a Poiseuille flow. Indeed, the boundary layer thickness decreases as Da decreases. Fig. 8 shows a remarkable drop in wall temperature of heat sink by inserting a MF on its free surface compared to an empty channel. MF intensified heat transfer due to its high thermal conductivity and porous structure that allows the fluid to pass through. Nusselt number is increased by a factor of 230% compared to an empty channel (see Table II)

TABLE I
METAL FOAM CHARACTERISTICS

PPI	40
Permeability K (m^2)	$6{,}78.10^{-7}$
Forchheimer Coefficient	0,1607

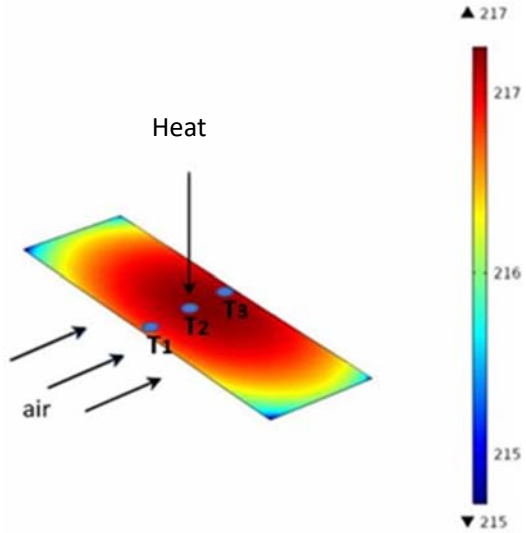

Fig. 5 Temperature field distribution on heat sink surface

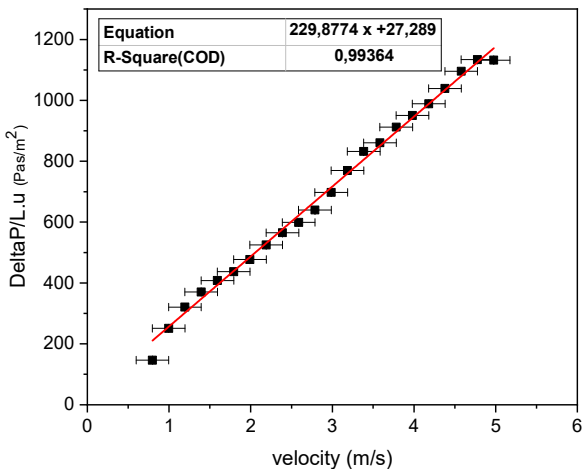

Fig. 6 Pressure loss variation in test section as a function of flow velocity in presence of a metal foam of dimension (10 × 30 × 20 cm)

Configuration III (empty channel with US) makes it possible to test the influence of acoustic streaming in a low flow rate

airflow without MF.

TABLE II
AVERAGE NUSSELT NUMBER VALUES AND THE ENHANCEMENT FACTOR IN AN EMPTY CHANNEL AND A CHANNEL WITH MF FOR A FLOW VELOCITY OF 0.4M/S AND A HEATING POWER OF 50 W

	Empty channel	Channel with MF
$\overline{Nu}$	40	132
η_{MF} (%)	230	

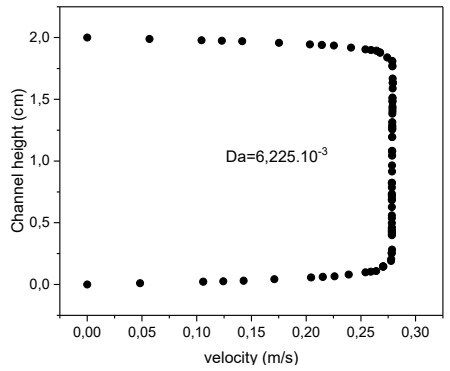

Fig. 7 Velocity profile through metal foam of dimension (10 × 3 × 2 cm), for a flow velocity of 0.4 m/s and a Darcy number equal to 6.225.10-3

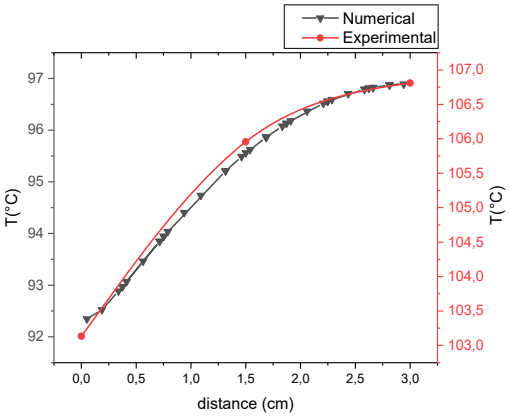

Fig. 8 Variation of wall temperature in the middle of heat sink in presence of a MF for a flow velocity of 0.4 m/s and a heating power of 50 W. T_{inlet} = 20 °C

Fig. 9 shows that ultrasound is able to improve heat transfer caused by the appearing of an acoustic streaming which impacts heat sink in different places, this phenomenon is responsible for increasing turbulence which probably allows injection of cold fluid at boundary layer where temperature is very high. As a result, acoustic stream mixes the core of the flow with viscous boundary layer. However, local Nu numbers of the order of 90 have been obtained at the exit of heat sink so that the acoustic streaming generated by the ultrasound is deflected by the main flow (due to the fan) towards this location (see Table III).

Configuration IV (channel with MF and US) is intended to illustrate the influence of MF and US on heat transfer. Fig. 10 shows that there is no change in wall temperature at heat sink after the ultrasound is switched on, which can be explained by the impedance of acoustic wave propagation medium. The difference in impedance between the two fluid-solid phases creates a phenomenon of refraction of transmitted wave and reflection of part of incident wave normal to the interface, which are responsible for convective aspect attenuation of acoustic streaming.

TABLE III
NUSSELT NUMBER VALUES AND THE ENHANCEMENT FACTOR IN AN EMPTY CHANNEL WITH AND WITHOUT US FOR A FLOW VELOCITY OF 0.4 M/S AND A HEATING POWER OF 50 W

	Empty channel	Empty channel with US
$\overline{Nu}$	40	55
η_{us} (%)	37,5	

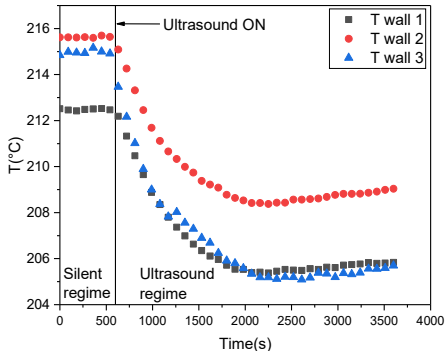

Fig. 9 Temporal evolution of heat sink wall temperature, with and without ultrasound obtained for a velocity of 0.4 m/s, an ultrasonic frequency of 40 kHz and a heating power of 50 W, Tempted = 20 °C

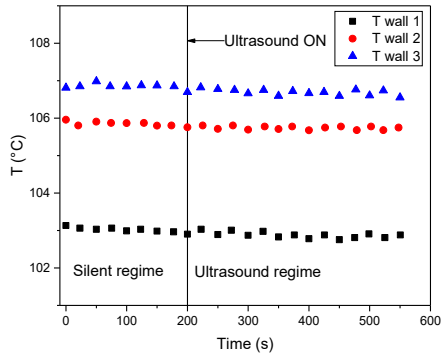

Fig. 10 Temporal evolution of heat sink wall temperature, without and with ultrasound obtained in presence of a metallic foam for a velocity of 0.4 m/s, an ultrasonic frequency of 40 kHz and a heating power of 50 W, Tempted = 20 °C.

V. CONCLUSION

This work was carried out with the aim of understanding the physical mechanisms behind the enhancement of heat transfers related to metallic foams and ultrasound in forced convection. The method adopted consists in following wall temperature evolution at the level of a heat sink on which is placed a 40PPI metallic foam exposed to 40 kHz ultrasounds responsible for the increase of heat exchange coefficients. Insertion of metal foam in a horizontal channel with a rectangular cross section improved heat transfer by a factor of 230% compared to an empty channel for a flow velocity of 0.4 m/s while an intensification factor of 37.5% was obtained by acoustic stream

effect generated by 40 kHz ultrasonic waves in an empty channel. The coupling of these two foam-acoustic wave intensification methods showed no influence of ultrasound on heat transfer, which can be explained by wave propagation medium impedance that attenuates acoustic stream effect.

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