Investigation of the Effect of a Synthetic Jet
on the Heat Transfer Coefficient

PETRA DANCOVA, TOMAS VIT, JAN NOVOSAD
Department of Power Engineering Equipment
Technical University of Liberec
Studentska 2, 46117 Liberec 1
CZECH REPUBLIC
petra.dancova@tul.cz

Abstract: This paper deals with the experimental investigation of heat transfer coefficient (HTC) and continues authors' previous research in a paper [1]. HTC is measured with using the thermoanemometry method on a heated plate on which impacts a synthetic jet. Those results are compared with HTC caused by impacted flow from a continual nozzle.
The thermoanemometer works in a constant temperature mode for both cases of experiments, and a glue film probe placed on the heated wall is used as a measuring sensor.

Key-Words: Synthetic jet, actuator, continual nozzle, heated plate, experiment, thermoanemometry, heat transfer, Nusselt number

1 Introduction

A phenomenon of heat transfer is intensively solved in these days. Especially cooling of electronics and micro-electronics devices is the important task. Each electronic device generates heat which grows proportionally with the number of components in a circuit. For the correct operation of the electronic devices, this heat has to be removed, the device should be cooled respectively. Cooling can be done in different ways, e.g.:

Passive coolers, they are designed with large surface (in form of lamellas, ribs or rods) and made from materials which are well to conductive heat (cooper, aluminum, etc.), [2].

Active coolers like fans generate the fluid flow from the environment. Very effective is the combination of active and passive coolers, [2].

Liquid cooling is a closed system with flowing heat exchange medium (most often distilled water or water modified to be non-electrically conductive, or in extreme cases a liquid operated at low temperatures such as liquid nitrogen or carbon dioxide). The circuit usually consists of a pump, individual coolers for chilled components and a large passive cooler (so-called "radiator"), [2].

Heat pipe is a hermetically sealed tube with the working substance (water, alcohol, propane butane, Freon, etc.) in form of a small amount of liquid substance and the rest of the tube is filled with its vapors. These heat pipes can transfer large heat outputs while maintaining a small temperature difference (typically around 2 °C). Heat transfer is based on evaporation and condensation, [3].

Peltier cells, i.e. thermoelectric cells which use the Peltier effect. The Peltier cell consists of two semiconductor bodies and a connecting bridge, which provide both power supply and absorption and radiating heat. Peltier cells are usually connected in series in larger units, the so-called cooling thermo-batteries. The advantage of Peltier thermo-batteries is the concentration of cooling or heating effect on a very small area and this area cooling is uniform, [4].

An alternative of cooling in micro-electronic systems can be the application of *synthetic jets*.

In micro-dimensions the flow is often laminar; therefore the heat transfer is small. Synthetic jets could be designed to disturb this laminar flow and intensify heat transfer, [5, 6]. Synthetic jets are often vectored perpendicularly to the surface to generate so-called impact flow, [7, 8].

The heat transfer is in most cases investigated indirectly using the heat and mass transfer analogy: mass transfer is measured and obtained data are recalculated to heat transfer using the ratio $Nu/Sh = (Pr/Sc)^n$, when Nu, Sh, Pr, and Sc is Nusselt, Sherwood, Prandtl, and Schmidt number, respectively. Exponent *n* in in range (0.33-0.42), [9]. Mass transfer can be obtained e.g. from the naphthalene sublimation, summarizing study can be found in [9].

In case of direct investigation of heat transfer, the other experimental methods then thermoanemometry are used like in [10] where the infrared thermography method is used.

Convective heat transfer investigation using thermoanemometry is described in paper [11].

List of selected symbols

CJ   jet from a continual nozzle
HTC   heat transfer coefficient (used in the text)
Re   Reynolds number
SJ   synthetic jet
TCR   temperature coefficient of resistance

D (m)   SJ actuator orifice diameter
D_C (m)   continual nozzle orifice diameter
D_D (m)   loudspeaker diaphragm diameter
E_{SJ} (V)   voltage measured on the probe wire with working SJ or CJ
E_0 (V)   voltage on the probe wire without influence from SJ, CJ respectively
H (m)   distance orifice – heated wall
h $(W \cdot m^{-2} \cdot K^{-1})$ heat transfer coefficient (used in the graphs)
Q_{diss} (W)   heat flux dissipated from the probe wire
q_{diss} (W/m^2) heat transfer rate
q_{cond} (W/m^2) heat transfer rate through the probe film
t_{wall} (°C)   heated wall temperature
t_{wire} (°C)   probe wire temperature
t_O (°C)   temperature at the orifice
T (s)   time period
U_0 (m/s)   time-mean orifice velocity of SJ

2 Experimental setup

For the HTC investigation two kind of impacted flows were used: synthetic jet and flow from the continual nozzle.

Synthetic jet (SJ) is generated by the periodical motion of an oscillating diaphragm, [12]. The SJ actuator consists of a sealed cavity equipped with two actuating loudspeakers Monacor SP 60/4 (D_D = 75 mm) and emitting orifice with diameter D = 10 mm. For the experiments, the loudspeakers were connected in parallel, i.e. in phase, and were fed with the sinusoidal signal with constant electrical power supply of 3 W. The working frequency corresponds to Eigen-frequency of the actuator and based on previous experiments in [1] it was set as 74 Hz.

The continual nozzle also consist from a sealed cavity (inner diameter of 46 mm, inner height of 44 mm) and emitting orifice (D_C= 4 mm). The air into the nozzle was supplied from the reservoir and was kept on constant conditions (air pressure from the reservoir, and output velocity from the orifice which was set with the system of valves).

The SJ or flow from the continual nozzle impacted on the aluminum plate (its dimensions were 350×260 mm). This wall was positioned in a distance of H from the SJ actuator or continual nozzle orifice. In these experiments, the SJ actuator, and the continual nozzle respectively, was placed on a traverser and moved in all three dimensions. The plate was mounted stationary. For the experimental setup see figure 1.

The plate was heated due to the heating foil (130×130 mm) firmly fixed on the bottom side of the plate. The foil was kept on the constant temperature which was controlled by a system of thermocouples connected into the PID regulator. All thermocouples were fastened in a part of the plate not influenced by the impact of the SJ, CJ respectively.

Temperature in the SJ actuator orifice t_{O_SJ}, CJ nozzle orifice t_{O_CJ} respectively was measured. HTC was calculated with respect to the orifice temperature t_{O_SJ} or t_{O_CJ}.
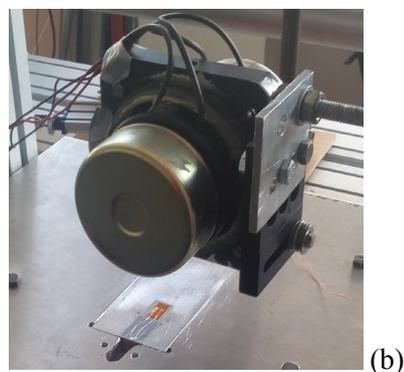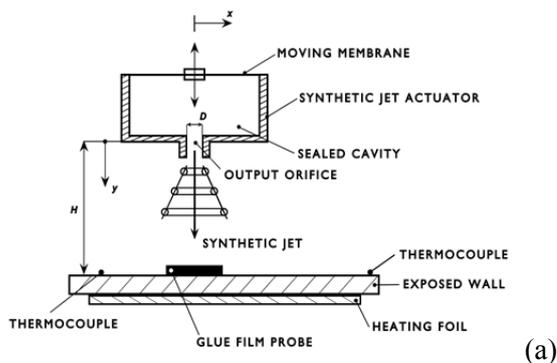

(a)

(b)

Figure 1. Experimental setup
(a) Schematic view, (b) SJ actuator, heated plate and glue film probe

3 Experimental method

The HTC and velocity of the flow was measured using the thermoanemometry method (in literature also called as *Hot Wire Anemometry*). For the thermoanemometry principle see Bruun [13].

Experiments were performed with thermoanemometer DANTEC 90C10 set in a constant temperature mode. HTC was investigated with a glue film probe DANTEC 55R47 fixed in the middle of an upper side of the heated plate. The sampling frequency and number of samples were set as 10 kHz, and 32,768 respectively. The temperature on the probe wire should be the same (or very close) as is the temperature set on the plate to prevent the conductive loses from the probe to the plate.

To compare the results of SJ and CJ, the right parameters of CJ were necessary to be set. Therefore the velocity measurements of SJ and CJ were performed using single wire probe DANTEC 55P11. Sampling frequency and number of samples were 10 kHz and 32,768. Calibration of the probe was carried out in the range (0.5-30.0) m/s. The error of the calibration was less than 2 %.

Raw data from thermoanemometry experiments were obtained as voltage. The phase averaging of the data during one cycle was performed by the decomposition $e(t) = E + E_P + e'$, where E, E_P, and e' (V) was the time-mean, periodic, and fluctuating component of measured quantity. During the SJ data analysis, it has to be taken into account that the thermoanemometric probes can measure only the absolute values of the flow. The SJ consists from the suction (negative values) and extrusion (positive values), therefore it is necessary to determine the direction of the flow in the phase of suction by data inverting.

The data processing was performed in software Matlab and Excel.

4 Results and discussion

4.1 SJ and CJ parameters settings

It is known, that SJ actuator works best near its resonance frequency, [12]. On this frequency the highest amplitude of extrusion velocity and mass flow rate is achieved at the given power. According to the authors' previous research in [1], the working frequency of the SJ actuator was set as 74 Hz for given electric power supply of 3 W.

To quantify the SJ, the time-mean orifice velocity U_0 and Reynolds number of SJ have to be determined as:

$$U_0 = \frac{1}{T} \int_0^{T_E} u_0(t)dt , \qquad (1)$$

$$\mathrm{Re}_{SJ} = \frac{U_0 D}{\nu} , \qquad (2)$$

where $u_0(t)$ (m/s) is the instantaneous velocity measured in the actuator orifice, for the sinusoidal waveform $u_0(t) = U_{\max} \sin(2\pi ft)$, f (Hz) is frequency, T (s) is time period, T_E (s) is time of extrusion (in our experiments $T_E = T/2$), ν (m²/s) is kinematic viscosity of the working fluid (air in our case).

The flow from the continual nozzle, i.e. the CJ velocity was set based on the equality of the Reynolds numbers of SJ and CJ.

Table 1 summarizes the parameters of SJ and CJ set during the experiments.

Table 1. Summarizing of SJ and CJ parameters

	SJ	**CJ**
D, D_C (mm)	10.0	4.0
Power supply (W)	3.0	-
f (Hz)	74.0	-
U_0 (m/s)	7.12	17.8
Re	4563	4563

Table 2. Temperatures set by the overheat ratio

Overheat ratio a	Orifice temperature t_O (°C)	Probe wire temperature t_{wire} (°C)	Plate temperature t_{wall} (°C)
SJ			
0.03	32.0	37.55	35
CJ			
0.03	18	36.55	35

4.2 Heat transfer investigation

Overheat ratio $a = 0.03$ was set for measurement of HTC. Based on the overheat ratio value and ambient temperature, the probe wire temperature was set and heated plate temperature determined. Determination of the plate temperature was also based on the equation (3):

$$T_{over} + T_a = T_{wire} \geq T_{wall} , \qquad (3)$$

where the sum of over temperature and ambient temperature is the probe wire temperature. To prevent the conductive loses from the probe to the wall, the wall and wire temperature difference should be less than 3 °C. The PID regulator ensures the settings of the heating foil temperature within the control band.

For summarizing temperature values relevant to the set overheat ratio see Table 2.

As was written above in chapter 3, obtained data are in form of voltage. Based on research in [1 and 14], these data should be processed with using following equations:

$$Q_{\text{diss}} = \left(E_{\text{SJ}}^2 - E_0^2\right) \frac{R_{sensor}}{\left(R_{\text{total}}+R_{\text{bridge}}\right)^2}, \qquad (4)$$

$$q_{\text{diss}} = \frac{Q_{\text{diss}}}{1.5 A_{\text{sensor}}}, \qquad (5)$$

$$h = \frac{q_{\text{diss}}+q_{\text{cond}}}{(T_{\text{w}}-T_{\text{O\_SJ}})}. \qquad (6)$$

Data obtained with working SJ, CJ respectively (E_{SJ} (V)) should be processed with data from the probe in operation when the flow did not impact on the heated plate (E_0 (V), eq. (4)). R_{sensor}, R_{total}, and R_{bridge} (Ω) in eq. (4) are resistance of the probe wire, whole system (total resistance) and Wheatstone bridge, respectively. As the working fluid is air, $R_{\text{bridge}} = 20\ \Omega$ for all experiments. R_{sensor} and R_{total} are set by the thermoanemometer system according to the overheat ratio, ambient temperature and temperature of the heated plate.

To quantify lateral conduction within the film of the probe (described in [15]), the multiplication of real probe area A_{sensor} (m^2) with a constant of 1.5 in denominator of eq. (5) is made. This multiplication gives the effective area of the probe wire.

Quantity of q_{cond} (W/m^2) in eq. (6) represents heat transfer rate through the probe film and depends on the probe wire and plate temperatures difference.

Before the experiment itself began, calibration of the film probe 55R47 had to be done. Figure 1 represents dependence of the total, and probe wire resistance respectively on ambient temperature. From this dependence, the probe wire TCR was received as $\alpha_{\text{wire}} = 0.34\ \%/°C$ (α_{wire} can be supposed as a constant because the dependence is linear).

Distribution of phase-averaged and time-mean HTC measured with set overheat ratio $a = 0.03$ in the distance $H = 10$ mm, i.e. $y/D = 1$ shows figure 2. The highest values of HTC are during the phase of extrusion ($t/T = 0.6$). Figure 3 demonstrates dependence of time-mean values of HTC measured at $a = 0.03$ on distance from the SJ actuator orifice. As was supposed the highest HTC value is on the plate positioned nearest to the orifice.
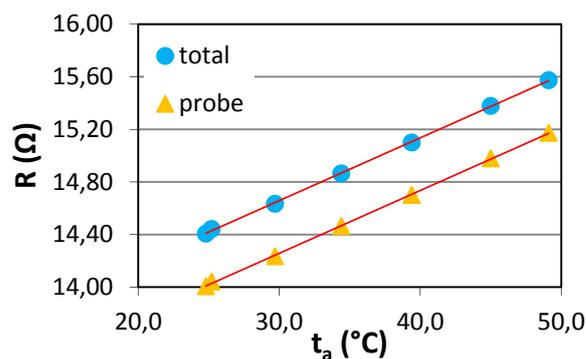

Figure 1. Dependence of the probe wire and total resistances on the ambient temperature

Dependence of HTC in different instances of the period in different distances from the SJ actuator orifice is visible in figure 4. The curves are shifter of 1500.

Figure 5 shows the time-mean values of HTC obtained for different distances from the continual nozzle orifice when overheat ratio was set as 0.03.

Figure 6 brings the comparison of HTC caused by SJ and CJ in distance $y/D = 1$. Three curves are visible on this figure: HTC caused by SJ in form of time-mean value (h_SJ) and phase of extrusion (0.6_SJ), and time-mean value of HTC caused by CJ (h_CJ). As was supposed, the SJ causes higher heat transfer on the heated plate that the CJ, especially during the phase of extrusion where the increase is more than 35 %.

5   Conclusions

This paper describes the research of heat transfer on a heated plate on which impacts the SJ. To determine the effect of the SJ, the heat transfer caused by the flow from the continual nozzle was also measured. The thermoanemometry method in the constant temperature mode was used.

According to the authors' previous experiments, the SJ actuator working frequency was set as 74 Hz on which all SJ experiments were performed. The time-mean orifice velocity and the Reynolds number of SJ were determined as $U_0 = 7.12$ m/s, $Re_{\text{SJ}} = 4563$, respectively. HTC was investigated for overheat ratios $a = 0.03$. The probe wire temperature and orifice temperature were set as 37.55 °C, and 32 °C respectively. The temperature of the heated plate was set as 35 °C.
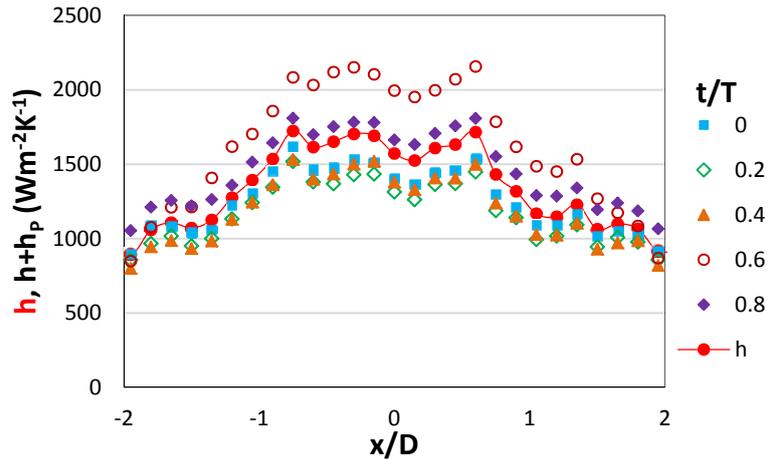
Figure 2. Distribution of the phased averaged HTC (h + h$_P$) and the time-mean HTC (h)
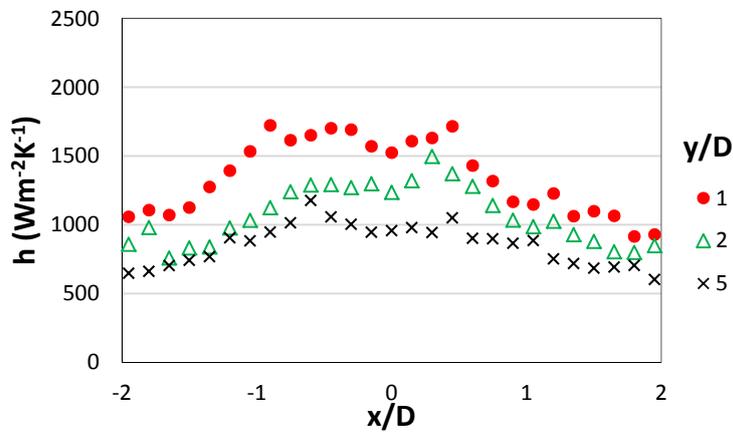a = 0.03, y/D= 1 (case of SJ)

Figure 3. Dependence of time-mean HTC on different distance from the SJ orifice, a = 0.03 (case of SJ)
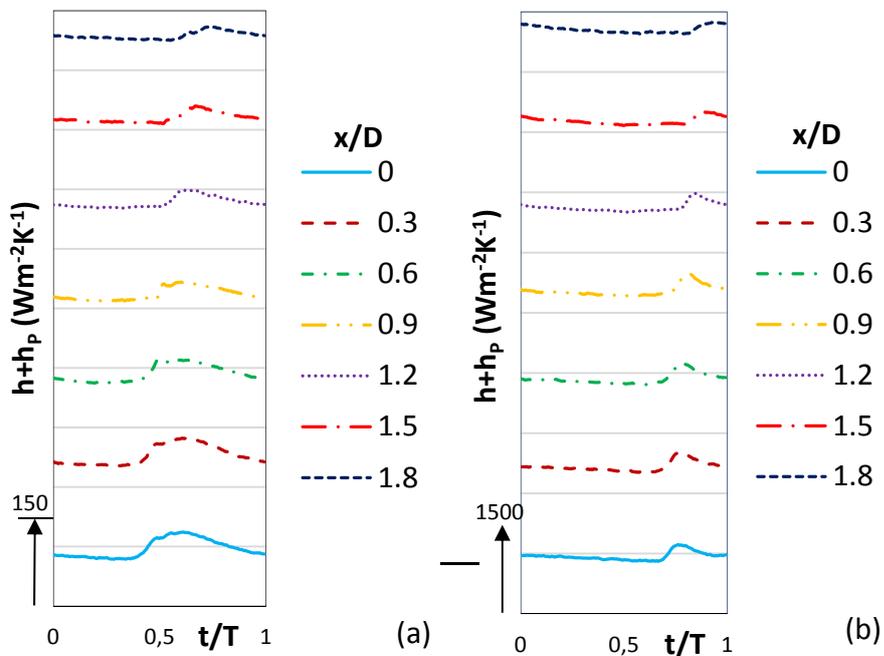

Figure 4. HTC as a function of time (t/T) and radial position on heated surface (x/D) during one period, (a)
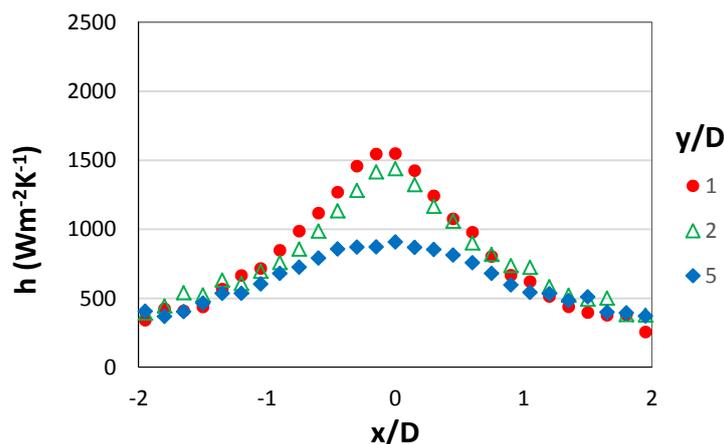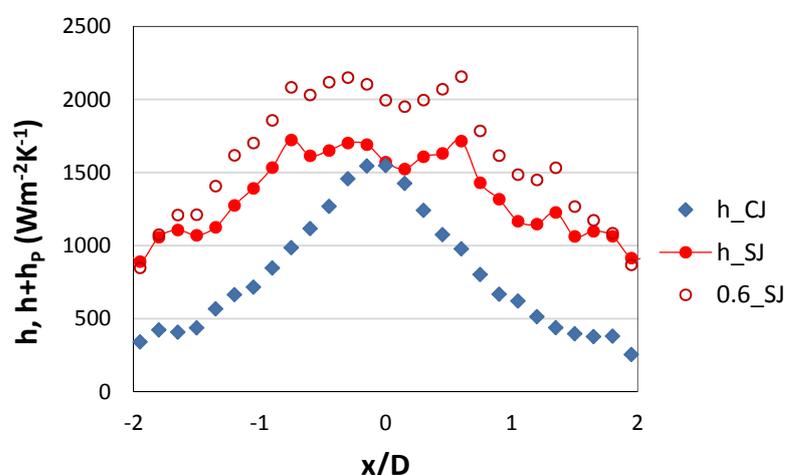y/D = 1, (b) y/D = 5 (case of SJ)

Figure 5 HTC time-mean values distribution, $a = 0.03$, $y/D = 1$ (case of CJ)

Comparison of time-mean values of HTC caused by SJ (h_SJ) and CJ (h_CJ) and phase averaged value (0.6_SJ) of HTC caused by SJ in distance $y/D = 1$

For comparison, the experiments of HTC were also performed using impacted flow from the continual nozzle. According to the equality of Reynolds numbers of SJ and CJ, the velocity of CJ was set as 17.8 m/s. During the HTC experiments, the settings of overheat ratio and heated plate temperature were set the same as for SJ experiments, i.e. $a = 0.03$, $t_{wall} = 35\,°C$. The probe wire temperature was set according to the overheat ratio and ambient temperature as 36.55 °C. As the working fluid for CJ the air from reservoir was used, the orifice temperature for this case was as 18 °C.

References:

[1] P. Dančová, J. Novosád, T. Vít, Investigation of the heat transfer coeeficient using a synthetic jet, *9th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics*, 12-15 June, 2017, Iguazu Falls, Brazil.

[2] https://www.thermacore.com/applications/electronics-cooling.aspx (cited 1.12.2017).

[3] http://www.wakefield-vette.com (7.11.2017).

[4] G. A. Mannella, V. La Carrubba, V. Brucato, Peltier cells as temperature control elements: Experimental characterization and modeling, Applied Thermal Engineering, Vol. 63, Issue 1, 2014, pp. 234-245.

[5] Z. Trávníček, P. Dančová, J. Kordík, T. Vít, M. Pavelka, M., Heat and mass transfer caused by a laminar channel flow equipped with a synthetic jet array, *Journal of Thermal Science and Engineering Applications*, Vol. 2, Issue 4, 2010.

[6] V. Timchenko, J.A. Reizes, E. Leonardi, F. Stella, Synthetic jet forced convection heat transfer enhancement in micro-channels, *Proceedings of the 13th International Heat Transfer Conference IHTC-13*, Sydney, NSW Australia. 2006.

[7] A. Pavlova, M. Amitay, Electronic Cooling Using Synthetic Jet Impingement, *J. Heat Transfer*, Vol. 128(9), 2006, pp. 897-907

[8] D.S. Kercher ; Jeong-Bong Lee ; O. Brand ; M.G. Allen ; A. Glezer, Microjet cooling devices for thermal management of electronics, *IEEE Transactions on Components and Packaging Technologies*, Vol. 26, Issue: 2, 2003, pp. 359-366

[9] R.J. Goldstein, H.H. Cho, A review of mass transfer measurements using naphthalene sublimation, *Exp. Thermal and Fluid Science*, Vol. 10, 1995, pp. 416-434.

[10] K. Petera, M. Dostál, T. Jirout, I. Fořt, Heat transfer similarities between impinging jets and axial-flow impellers, *Theoretical Foundations of Chemical Engineering*, Vol. 50, No. 6, 2016, pp. 937-944.

[11] J.W. Scholten, D.B. Murray, Measurement of convective heat transfer using hot film sensors: Correction for sensors overheat, *Journal of Heat Transfer*, Vol. 118, 1996, pp. 982-984.

[12] B.L. Smith, A. Glezer, The formation and evolution of synthetic jets, *Phys. Fluids*, Vol. 10, 1998, pp.2281-2297.

[13] H.H. Bruun, *Hot wire anemometry*, Oxford Univ. Press, 1995

[14] J.W. Scholten, D.B. Murray, Unsteady heat transfer and velocity of a cylinder in cross flow- I. Low freestream turbulence, *Int. J. Heat Mass Transfer*, Vol. 41, 1997, pp. 1139-1148.

[15] D.E. Beasley, R.S. Figliola, A generalized analysis of a local heat flux probe, *J. Physics E.*, Vol. 21, 1988, pp. 316-322.