Experimental analysis of heat transfer between a heated wire and a rarefied gas in an annular gap with high diameter ratio

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Abstract. In this paper a first experimental attempt is performed to measure heat conduction through rarefied air at rest contained between two concentric cylinders. The heat transfer between a heated platinum wire having a diameter (d) of 0.15 mm, disposed along the axis of a cylindrical shell in stainless steel having an inner diameter (D) of 100 mm, and a surrounded rarefied gas has been studied experimentally and numerically. The ratio between the outer and inner diameter of the annular region filled by the gas is large (D/d=667). In the annular region filled with air the pressure was varied by using a vacuum pump from atmospheric value down to 10⁻³ mbar. Temperature differences between the wire and the external stainless steel wall in the range 50-125 K were imposed and the heat power transferred from the wire to the surround was measured as a function of the gas pressure starting from air at atmospheric conditions down to 10⁻³ mbar. The experimental results obtained in these tests were compared with the numerical results obtained by using the linear and nonlinear Shakhov kinetic models.

1. Introduction
During the last decades the development of innovative miniaturised sensors has been constantly increasing due to the rapid improvement of the micro-fabrication technologies. The reduction of the dimensions of the sensors has found various interests in a large spread of technological fields. Indeed, together with the sensor reduction, this kind of new sensors make it possible to reduce their impact on the measured system, the power consumptions of the active components, their characteristic response time and, in many cases, their cost. In particular, the microsensors based on silicon with on-chip circuitry fabricated by using the integrated circuit (IC) technology have demonstrated that it becomes possible to conjugate low costs with high level of reliability and the compatibility with the modern signal processing circuitry. A variety of microsensors and microactuators fabricated by standard semiconductor technologies have been demonstrated in the last ten years: an important field of application of these miniaturized sensors is related to the measurement of the gas pressure (micro-Pirani sensors [1]), especially in the range between 1 and 10⁻⁵ mbar; the miniaturization of the Pirani sensors has enabled the extension of their dynamic range measurement in comparison to the classical

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Pirani gauges. The microPirani sensors are sometimes based on silicon sheets realizing plate geometries and sometimes based on a hot wire with a diameter of the order of hundreds of microns inserted in a system having a characteristic dimension of the order of some centimetre with a large scale difference between the wire and its surround. The heat transfer between the wire and its surround can be modelled by considering the problem of heat conduction through rarefied gases contained between two concentric cylinders. This kind of geometry has been extensively investigated in the past, for practical reasons, in order to measure thermal conductivities and thermal accommodation coefficients of gases. One of the first experimental work in this field is due to Bomelburg [2] on 1959, who measured heat conduction from 1.25, 5 and 10 μm diameters Wollaston wires placed in 10 and 25 cm inner diameter bell jars. In these experiments the author assumed thermal radiation and end losses as negligible. Dybbs and Springer [3] evidenced as the conditions of the experiments of Bomelburg had to be improved. Their experimental tests were conducted by using helium, neon and argon over a pressure range that included free molecular, transitional and temperature jump regimes. Special care was dedicated by the authors in order to design a test rig in which the effects due to end losses can be minimized and in order to eliminate the effect related to thermal radiation between the heated wire and surround. The experimental results obtained by Dybbs and Springer were in a good agreement with the numerical results obtained by using the momentum method proposed by Lees and Liu [4] over the entire Knudsen number range covered in the experiments (0.02<Kn<50), assuming that the thermal accommodation coefficient at the inner cylinder remained constant over this range at its free molecular value. Yu et al. [5] proposed a transient hot-wire technique in order to measure the heat flux between a fine metallic filament (platinum, nickel, tungsten, tantalum) and a rarefied gas under different heat transfer conditions ranging from a molecular to a continuum regime. Their data have been compared with the theoretical ones obtained from the solution of the BGK model by the variational method and the comparison evidenced a very good agreement between experimental and numerical values.

More recently, O'Shea and Collins [6] measured the total heat losses due to conduction heat transfer through rarefied polyatomic gas (benzene and n-hexane) in a concentric cylindrical geometry in order to study the heat transfer in temperature limited evacuated solar thermal collectors. Their experimental data have been compared with the results obtained by means of a Monte Carlo simulation in the range of Knudsen numbers between 0.1 and 100 showing a good agreement for annular gaps of the order of 2.65 mm and 2.1 mm and for an imposed temperature difference between the inner cylinder and the outer cylinder equal to 60 K.

From the analysis of the literature it is evident that a large part of the experimental results published in this area are more than 40 years old.

In addition, the more accurate experimental data appeared in literature have been obtained:

1. by imposing low temperature differences between the heated wire and the surround (ΔT<10 K) [2,3,5];
2. by considering low values of the ratio between the diameter of the external cylinder (D) and the diameter of the heated wire (d) [3,5,6].

The work presented in this paper has the goal to remove these two limitations by increasing the temperature difference between the wire and the surround up to 140 K and by adopting a cylindrical geometry characterised by a large value of the D/d ratio (equal to 667). The experimental results are compared to corresponding computational ones based on linear [7] and nonlinear [8] kinetic theory in order to analyse the validity of kinetic modelling and to appreciate the deviation from the linear theory which can be evidenced experimentally when the imposed temperature difference between the wire and the external shell increases. These preliminary results will be extended and validated in the short future in order to be used as a benchmark for the test rig that will be further used in order to investigate the behaviour of this system under transient conditions.

2. The experimental test rig
In order to study the heat transfer between the wire and a surrounded rarefied gas an experimental campaign has been conducted at the Laboratory of ENEA in Rome (Italy) with the cooperation of the
DIENCA Microfluidics Lab (Bologna, Italy). A specific test rig (RAGA) has been designed and realized in order to test the heat conduction between a heated platinum wire and rarefied air within a stainless steel cylinder (Figure 1).

In Figure 1 is shown the cylindrical test section used in this experience. A stainless steel cylindrical capsule having an inner diameter ($D$) equal to 100 mm and a total length of 400 mm; it contains a platinum wire ($I$, Fig. 1) fixed between two Teflon blocks ($2$, Fig. 1). The wire has a diameter ($d$) of 0.15 mm and a length ($L$) of 97 mm.

![Figure 1. Sketch of the RAGA test rig: the cylindrical capsule with the centred platinum wire.](image)

The platinum wire is fixed to a rectangular support, shown in Figure 2a, which maintains the wire on the axis of the capsule. The wire is placed in the central region of the capsule in order to minimize the effects related to the ends of the cylindrical chamber. The wire is soldered to two copper ends, having the first a diameter of 1.45 mm ($d_1$), a length of 10.55 mm ($L_1$) and the second a diameter of 1.7 mm ($d_2$) and a length of 9.75 mm ($L_2$); on these copper ends the electrodes used to heat by Joule effect the wire are attached (see Figure 2b). The Teflon blocks reduce the heat losses at the ends of the heated section. The geometry of the cylindrical test rig is characterized by a very large ratio between the outer and inner diameter of the annular region filled by the gas ($D/d=667$).

![Figure 2. The platinum wire fixed to the rectangular support by means of two teflon blocks (a); the copper end soldered to the platinum wire where the electrical electrode is fixed (b).](image)

The cylindrical capsule is filled with air, initially at the atmospheric pressure. By connecting the capsule to the backing pump of a turbo-molecular pump ($Alcatel ATS-100$) it is possible to reduce the air pressure from atmospheric value down to $10^{-3}$ mbar. The pressure inside the capsule was monitored by means of a vacuum pressure gauge ($MKS type 925$).

The platinum wire is heated by Joule effect using a programmable DC supply ($HP6032A$) which provides a constant electrical current on the wire. The electrical resistance of the Pt wire varies with...
the average wire temperature between 0.12 and 0.39 ohm; the maximum value of electrical power which has been imposed on the wire during the tests is of the order of 700 mW. The programmable DC supply was managed by using LabView in order to impose a fixed value of the average temperature along the wire surface.

The temperature along the platinum wire was measured by means of 5 K-type thin thermocouples, having a diameter of 25 µm, glued directly on the wire surface (Figure 3a). By means of Joule heating, the wire temperature was varied up to 150°C; on the contrary the external tube is maintained at the room temperature (25-27°C). The maximum value of temperature of the wire was selected by taking into account the working range of the glue used to fix the thermocouples on the wire. The temperature of the external stainless steel tube was monitored by means of 3 K-type thermocouples (Figure 3b). During the experience large values of the temperature difference between the wire and the external stainless steel wall of the capsule (ΔT) were imposed ranging between 50 K to 125 K.

![Figure 3. 5 K-type thermocouples glued on the platinum wire (a); 3 K-type thermocouples attached on the inner surface of the stainless steel external capsule.](image)

In Table 1 the typical uncertainty of the sensors used in these tests is quoted.

| Instrument            | Range       | Uncertainty     |
|-----------------------|-------------|-----------------|
| K-type thermocouples  | 0-200°C     | ±0.1 K          |
| Pressure gauge        | 10⁻¹⁻¹⁻¹⁻¹ mbar | ±10% R (10⁻¹⁻¹⁻¹⁻¹ mbar) ±5% R (10⁻¹⁻¹⁻¹⁻¹⁻¹ mbar) |
| Electrical current    | 0-17 A      | ± 0.36% R + 15 mA |
| Voltage               | 0-200 V     | ± 0.08% R + 80 mV |

Before making measurements the system was evacuated, backed out and the main filament was flashed. After that, the tests were conducted by following these steps:
1. A value of pressure is fixed inside the cylindrical shell, starting from atmospheric value.
2. By means of the DC programmable supply (*HP6032A*) a value of electrical current is imposed through the platinum wire in order to maintain the average temperature of the wire equal to the set-point (*T*sp*). A LabView code was used in order to tune the supply by using the temperature measurements on the wire. The LabView system is set in order to verify that the measured
average value of the wire temperature (calculated as average value of the 5 values of temperature measured by the K-type thermocouples ($T_{w,i}$) glued on the wire surface (Fig. 3a)), is maintained by the DC programmable supply within 2% from the imposed set-point ($T_{sp}$):

$$\frac{\delta T}{T_{sp}} = \frac{\sum_{i=1}^{5} T_{w,i} - 5T_{sp}}{5T_{sp}} \leq 0.02$$  \hspace{1cm} (1)

3. The value of the electrical power dissipated through the platinum wire for Joule heating is calculated as product between the square value of the imposed electrical current (range: 0.2-0.7 A) and the wire electrical resistance ($R$):

$$Q = I^2 R$$  \hspace{1cm} (2)

In steady-state conditions the power $Q$ is equal to the heat transferred from the wire to the surround by radiation and conduction:

$$Q = I^2 R = g(p_{gas})Q_{cond} + Q_{rad}$$  \hspace{1cm} (3)

where $g(p_{gas})$ is a correction factor of the heat conduction term depending on the rarefaction level of the air within the vacuum chamber.

The radiative term is independent on the gas pressure within the vacuum chamber and it is evaluated by considering the formula for two concentric cylindrical surfaces [9], simplified for the limiting case where the surface of the internal body (OD of the platinum wire is 0.15 mm) is much smaller than the external, concave surface (ID of the vacuum chamber is 100 mm):

$$Q_{rad} = \sigma_0 A(T_{sp}^4 - T_{ext}^4)$$  \hspace{1cm} (4)

where $T_{sp}$ is the imposed wire temperature, $T_{ext}$ is the temperature of the inner surface of the stainless steel capsule (obtained as average value of the temperature measured by the 3 K-type thermocouples of Fig.3b) and $A$ the radiative total surface of the heated section calculated as follows:

$$A = \varepsilon_w \pi dL + \varepsilon_c \left( \pi d_1 L_1 + \pi d_2 L_2 \right) + \varepsilon_c \frac{\pi}{4} \left( d_1^2 + d_2^2 - 2d^2 \right)$$  \hspace{1cm} (5)

$\varepsilon_w$ is the emissivity of the platinum wire ($\varepsilon_w =0.05$) and $\varepsilon_c$ is the emissivity of the oxidized copper ends ($\varepsilon_c =0.53$). The values of the emissivity of the platinum wire and of the copper ends have been checked by comparing the surface temperature of the components measured by an infrared camera (AVIO TVS 200EX) and by means of a thermocouple glued on the surface: the value of the emissivity has been tuned in order to obtain the same value of temperature indicated by the thermocouple. The emissivity values were checked before each experimental test. The accuracy linked to the estimation of the emissivity obtained with this method is not very high and can be estimated of the order of ±10%; however, the estimated emissivity of platinum and copper are in agreement with the literature values [10].

The heat loss due to conduction through the air is written in Eq.(3) as a product between the classical conduction term ($Q_{cond}$) and a correction factor $g(p_{gas})$, depending on the rarefaction level of the air, which reduces the conduction heat transfer when the gas pressure decreases:

$$g(p_{gas})Q_{cond} = g(p_{gas})\lambda_0(T_m) \frac{\Delta T}{\ln(D/d)}$$  \hspace{1cm} (6)

where $\Delta T= T_{sp} - T_{ext}$ and $\lambda_0$ is the air thermal conductivity at atmospheric conditions and at the average temperature between the wire and the capsule ($T_m=(T_{ext}+T_{sp})/2$), calculated as a function of temperature by means of the following correlation ($T_m$ in K):

$$T_m = \frac{T_{sp} - T_{ext}}{\frac{\lambda_0(T_m)}{2 \pi L}}$$
\lambda_q(T_m) = -0.00039333 + 1.0184 \cdot 10^{-4} T_m - 4.8574 \cdot 10^{-8} T_m^2 + 1.5207 \cdot 10^{-11} T_m^3 \left[ \frac{W}{mK} \right] \tag{7}

Eq.(7) gives values of the air thermal conductivity in the range 0-200°C with a maximum overestimation of the values quoted in Raznjevic [11] equal to +4.2%.

Since the radiative term is independent on the gas pressure for a fixed wire temperature and capsule inner temperature, the weight of thermal radiation is not negligible especially at low gas pressure where the conduction heat transfer is strongly reduced by rarefaction.

From Eq.(3) it is evident that, for a fixed wire temperature \(T_{sp}\) and capsule temperature \(T_{ext}\), \(Q\) is a function of the air pressure within the capsule.

4. By means of the valve between the turbo-molecular pump and the stainless steel capsule the gas pressure was progressively reduced and the value of \(Q\), evaluated by using Eq.(1), was recorded as a function of the air pressure in the chamber.

5. All the operative procedure is repeated by changing the set-point temperature of the wire.

3. The linear and non linear Shakhov kinetic model

The specific heat transfer configuration may be accurately simulated in the whole range of the Knudsen number via the Shakhov (S) kinetic model. Taking into account the axisymmetry of the problem and invariance in the axial direction (i.e. ignoring end effects) the S kinetic equation reads [7,8]

\[ \xi_p \cos \theta \frac{\partial f}{\partial \hat{r}} - \frac{\xi_p \sin \theta \partial f}{\hat{r}} = \frac{P}{\mu} \left( f^S - f \right) \tag{8} \]

where

\[ f^S = f^M \left[ 1 + \frac{2m}{15n(k_B T)} q \xi_p \cos \theta \left( \frac{m \xi^2}{2k_B T} - \frac{5}{2} \right) \right] \tag{9} \]

with

\[ f^M = n \left( \frac{m}{2 \pi k_B T} \right)^{3/2} \exp \left( -\frac{m \xi^2}{2k_B T} \right) \tag{10} \]

being the Maxwellian.

Here, \( f = f(\hat{r}, \xi) \) is the unknown distribution function, \( \hat{r} \) is the radial spatial coordinate and \( \xi = (\xi_p \cos \theta, \xi_p \sin \theta, \xi_z) \) is the molecular velocity vector. Also, \( n, T \) and \( q \) are the macroscopic distributions of number density, temperature and radial heat flux respectively, which may be obtained by the moments of the distribution function according to

\[ n(\hat{r}) = \iint f \xi_p d\xi_p d\theta d\xi_z \tag{11} \]

\[ T(\hat{r}) = \frac{m}{3n(\hat{r}) k_B} \iint \xi^2 \xi_p f \xi_p d\xi_p d\theta d\xi_z \tag{12} \]

\[ q(\hat{r}) = \frac{m}{2} \iint \xi^3 \cos \theta \xi_p f \xi_p d\xi_p d\theta d\xi_z \tag{13} \]

Furthermore, \( \mu \) is the viscosity of the gas at local temperature \( T \), while \( P \) is the local pressure of the gas given by the equation of state \( P=nk_B T \), with \( k_B \) denoting the Boltzmann constant.

When the temperature difference between the wire and the external stainless steel wall, namely \( \Delta T = T_{sp} - T_{ext} \) is small compared to \( T_0 = T_m = (T_{sp} + T_{ext}) \) / 2 the unknown distribution function may be linearized according to:
to yield the corresponding linearized S kinetic equation with the associated perturbed macroscopic quantities [7].

It is noted that both the linear and nonlinear heat transfer problem under consideration have been recently solved in [7] and [8] respectively deducing accurate results in the whole range of gas rarefaction for various radius ratios and temperature differences. All the details may be found in these references. Here, these kinetic algorithms are implemented to yield the linear and nonlinear heat fluxes for the specific radius ratio $D/d = 667$ and the imposed temperature differences $\Delta T$ of the experimental set-up. Based on these results a comparison between computations and measurements is performed in the next section.

4. Discussion of the results

The raw data obtained during these tests are shown in Figure 4. It is possible to distinguish 4 series of data obtained by imposing a temperature difference between the wire and the inner surface of the vacuum chamber equal to 50 K, 75 K, 100 K and 125 K.

![Figure 4](image)

**Figure 4.** Heat power ($Q$) as a function of the gas pressure within the capsule for different values of the imposed $\Delta T$ (a); $Q$ compared with the radiative and the conductive terms for an imposed $\Delta T=100$ K (b).

By observing Figure 4a it is evident that $Q$ tends to saturate both for low and large values of gas pressure. When the air pressure is larger than 1 mbar the heat power $Q$ transferred from the heated wire to the surround becomes independent by the gas pressure: the heat is mainly transferred by conduction ($Q=Q_{\text{cond}}$). On the contrary, when the level of the gas rarefaction increases, the conduction becomes less efficient as heat transfer mode and it tends to become negligible; for this reason, the heat transfer for gas pressure less than 0.01 mbar is mainly due to the radiative component ($Q=Q_{\text{rad}}$) which is independent by the gas pressure (see Figure 4b).

Figure 4b highlights that, even in the case of a large temperature difference between the wire and the inner surface of the capsule ($\Delta T=100$ K), the effects due to natural convection was very low within the chamber; in fact, the heat power $Q$ is close to $Q_{\text{cond}}$ when the gas pressure increases. In the case of Figure 4b the difference between $Q$ and $Q_{\text{cond}}$ is small and entirely due to the presence of the radiative heat transfer component. The same observation can be repeated for $\Delta T=50$ K, 75 K, and 125 K. It is possible to conclude that the effects due to natural convection within the capsule in the range of temperature difference tested in this experimental campaign are very limited.

In Figure 5a the difference between the measured wire temperature and the imposed temperature set point is shown for the 4 series of tests conducted in this work. It is well evident that the system is able to guarantee a maximum difference between the measured temperature of the platinum wire and the
set point less than ±2% during the whole experimental conditions. As general trend, the platinum wire was maintained to a temperature lower than the set-point when the air pressure in the chamber decreases down to 0.1 mbar; on the contrary, the wire temperature was larger than the set-point for large gas pressure.

In Figure 5b is shown the trend of the temperature difference between the wire and the stainless steel shell during the experimental test. It can be evidenced that the variation of ΔT is for a large part of data within 3% during the tests but, in some case a maximum variation equal to ±5% is reached. This variation is due to the choice to leave free the temperature of the external shell which is exposed to the variation of the room thermal conditions. This fact has to be considered during the discussion of the results since it determines a limitation in terms of accuracy of the results.

The numerical results obtained by the Shakhov kinetic model neglect the radiative heat transfer between the wire and its surround. In order to compare the numerical data with the experimental results it is important to subtract the radiative heat transfer component (which is independent by the gas pressure) to the value of the heat power calculated by using Eq.(1). In Figure 6 the difference $Q - Q_{\text{rad}}$ is shown as a function of the gas pressure and compared with the predictions of the linear S model described in the previous section.

It is evident that the agreement between the numerical data and the experimental data is quite good for ΔT=50 K in the whole range of pressure investigated (see Figure 6a). When the temperature difference between the wire and surround increases (Figure 6b,c,d), the agreement between the experimental values and the numerical data tends to decrease. In particular, when the temperature difference increases the linear S method seems to underestimate the heat transfer between the wire and the gas. It is noted that the kinetic results have been obtained assuming purely diffuse reflection at the wall, i.e., the accommodation coefficient is taken equal to one ($\alpha=1$), while a reduction in the value of $\alpha$ will further reduce the computed heat transfer.

In order to check if this difference is contributed to the implementation of linear modelling a comparison with nonlinear results is presented in Fig. 7 for ΔT=100 K. As it is seen for pressure values up to 0.2 mbar the linear and nonlinear results are identical while for the higher pressure values the nonlinear heat fluxes tend to become larger and closer to the experimental ones. This behaviour is expected since in this case the ratio $\Delta T/T_0$ is about 0.3, in which case there are no large differences between linear and nonlinear analysis. On the contrary, the experimental results put in evidence some difference with the theoretical predictions also for low values of pressure. Thus, the results shown in Figure 7 underline that the discrepancy between computations and measurements cannot be contributed solely to the differences between linear and nonlinear analysis.
Figure 6. Comparison between experimental values and numerical data: (a) \(\Delta T=50\) K; (b) \(\Delta T=75\) K; (c) \(\Delta T=100\) K; (d) \(\Delta T=125\) K.

Figure 7. Comparison between experimental values and nonlinear numerical data for \(\Delta T=100\) K.

It is important to underline that in the numerical kinetic solution adopted in this work, air is considered as a pure monoatomic gas since the authors have found very good agreement with experiments with nitrogen and air in their previous works [12]. However, since in this experimental work the humidity of air was not checked and measured, the water content could be responsible of a deviation of the data.
from the theoretical prediction (obtained for pure air). In addition, it is important to bear in mind that during the experience the temperature difference between the wire and the external shell can vary of ±5%, as highlighted by Figure 5b; on the contrary, the numerical results have been obtained by imposing a fixed value of ΔT. From a geometrical point of view, a possible explanation of the disagreement between the numerical predictions and the experimental data is linked to the break of symmetry introduced by the metallic holder for the wire (see Fig.2). Another sensible point of this experience is linked to the accurate determination of the emissivity of the wire and its copper supports which, as the experimental results confirm, play an important role on the accurate determination of the total heat transferred to the surround, especially when the wire temperature increases. All these observations, put in evidence how, at the present stage, the designed test rig cannot be considered able to check in which conditions non-linear results begin to deviate from the linear ones. Further experimental tests and numerical runs have been planned in the short future in order to improve the test rig and generate new and more accurate experimental data.

5. Conclusions
In this paper an experimental and numerical analysis of the heat conduction between a heated platinum wire having a diameter (d) of 0.15 mm, disposed along the axis of a cylindrical shell in stainless steel having an inner diameter (D) of 100 mm filled with air is described. Temperature differences between the wire and the external stainless steel wall in the range 50-125 K were imposed and the heat power transferred from the wire to the surround was measured as a function of the gas pressure starting from air at atmospheric conditions down to 10⁻³ mbar. The experimental results obtained in these tests were compared with the numerical results obtained by using the linear and nonlinear Shakhov kinetic models. It has been observed a good agreement between the numerical results obtained using the linear S kinetic model and the experimental results for ΔT=50 and 75 K; on the contrary, for ΔT>75 K the experimental heat flux was larger than the numerical values. The comparison with the predictions obtained for ΔT=100 K using the non-linear Shakhov kinetic model evidenced how the non-linear model can improves the agreement with the experimental results solely for pressure larger than 0.2 mbar. On the contrary, for lower pressure the larger experimental heat fluxes cannot be justified by invoking non-linear effects. These results suggest the need of an improved accuracy in the experimental tests in order to check in which conditions non-linear results begin to deviate from the linear ones.

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References
[1] Górecka-Drzazga A 2009 Vacuum 83 1419
[2] Bornelburg HS 1959 Phys. Fluids 2 717
[3] Dybbs A, Springer GS 1965 Phys. Fluids 8 1946
[4] Lees L, Liu CY 1962 Phys. Fluids 5 1137
[5] Semyonov YG, Borisov SF, Suetin PE 1984 Int. J. Heat Mass Transfer 27 1789
[6] O'Shea SJ, Collins RE 1992 Int. J. Heat Mass Transfer 35 3431
[7] Sharipov F, Bertoldo G 2006 J. Vac. Sci. Technol. A 26 2087
[8] Shakhov EM, 1968 Fluid Dynamics 3 142
[9] Incropera FP, DeWitt DP, Bergman TL, Lavine AS 2007 Introduction to Heat Transfer, Wiley & Sons Ed.
[10] Siegel JR, Howell R, Howell. JR 2001 Thermal radiation heat transfer Taylor & Francis Ed.
[11] Raznjevic K, Handbook of Thermodynamic Tables and Charts, 1976 McGraw-Hill Ed.
[12] Pantazis S, Valougeorgis D, 2010 Eur.J. Mech. B/Fluids 29 494