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Simulation of Characteristics of Thermo-Hydraulic Process in Porous-Net Matrix of Rotary Heat Exchanger

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Abstract

This article discusses simulation of thermo-hydraulic characteristics of porous-net matrix of rotor heat exchanger with conic heat transfer elements of transport gas-turbine low-power engine. Heat transfer processes in porous-net matrix are studied insufficiently, which creates considerable difficulties for designing of heat exchangers. Thermo-hydraulic processes in porous-net matrix composed of 10 layers of metallic mesh wire used in heat transfer elements of rotor heat exchangers have been simulated. The obtained results have been used for development of relationships describing heating and cooling in porous-net matrix as a function of parameters of heat carrier flow differing from the known relationships. In order to approbate the obtained equations the heat recovery rate in rotor heat exchanger with a 270 kW transport microturbine have been calculated by means of mathematical simulation of thermo-hydraulic processes in porous-net matrix. The calculations of the heat recovery rate of the given heat exchanger using verified temperature dependences of the Colborne factor demonstrate good agreement with experimental data in the range of one and a half percent.

AMS subject classification:
Keywords: Microturbine, heat exchanger, porous net matrix, heat transfer.

1. Introduction

Nowadays centralized power supply (heat and electricity) in Russia is partially transferred to distributed power supply, based in small-size heat power plants running on gas and renewable energy sources (biogas and others) [14, 21]. This is caused by increase in demand for energy sources by consumers of relatively low power, increase in the scope of residential construction and increased portion of low-height buildings, vast territories not covered by centralized systems of electricity and gas supply, low densities of electric loads in vast territories with running centralized electricity supply, long distance of deteriorated power supply lines in the areas of low loads, high investments upon erection of heat pipelines, as well as high losses upon their operation and others.

Similar trends of heat power engineering can be met in Western countries [2, 4].

The range of promising heat power miniplants is as follows: power assemblies running on inexpensive fuel (natural gas) on the basis of piston gas engines and microturbines. The microturbines require significantly lower technical maintenance. For instance, Russian heat power plant on the basis of piston internal combustion engines are characterized by maintenance at the intervals of 1000-1500 motor hours (6-8 times per year). Current maintenance of Capstone microturbines (one of the leading US microturbine manufacturer [5, 6]) is performed at working site once per year and requires external examination, replacement or cleaning of air filter.

One of the most important elements of microturbines is heat exchanger. Such heat exchanger provides sufficiently high efficiency for modern microturbines (electrical efficiency of microturbine power plants is in the range of 29-34%). Installation of heat exchanger in microturbine leads to significant decrease in its dimensions and weight. Therefore, the issue of development of high efficient compact heat exchanger is quite urgent upon designing of microturbines. At present microturbines are equipped mainly with stationary recuperative heat exchangers [3, 5, 6, 8–11, 17, 23].

In addition, the activities devoted to rotor heat exchangers are under way. This is related with their perfect compactness and efficiency. The works [16, 25–28] are devoted to development of high-temperature and high efficient microturbines on the basis of ceramic rotor heat exchangers. The main bottleneck of ceramic rotor heat exchangers is low efficiency of their sealing, air leakage in them reaches 6%. In such heat exchangers this is caused by the contact between the sealing and porous ceramic matrix. In order to provide sufficient resource the sealing is pressed against porous matrix at low pressure, which leads to very high leakage of compressed air (up to 6%) [25–28].

Cooled metallic framed rotor heat exchangers can also be applied in high-temperature microturbines (Fig. 1) [1, 13]. In such heat exchanger sealing is pressed against cooled flat framed surfaces. Such design provides insignificant air leakage via sealing of rotor heat exchanger in the range of 1–1.5%.

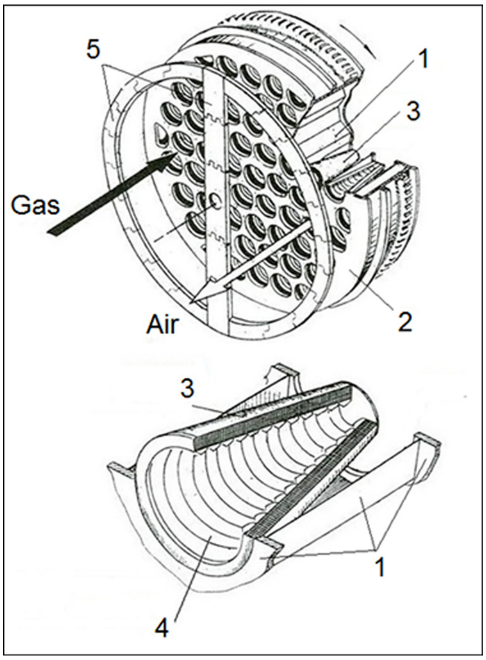

Figure 1: Rotor framed heat exchanger with conic heat transfer elements made of steel fine mesh wire screen: 1 – framework, 2 – flat framework surface for installation of sealing, 3 – porous-net conic heat transfer element, 4 – distributing (guiding) grid, 5 – sealing of rotor heat exchanger.

2. Experimental

One of the variants of cooling of framework of rotor heat exchanger is fabrication of conic heat transfer elements. In this case almost all framework surface upon operation of heat exchanger is flushed only by cold outside air supplied to heat exchanger at 450–470 K and transferred via conic heat transfer element, thus, cooled to 520–540 K by gas.

In such heat exchangers the conic heat transfer element is formed by rolled metallic mesh wire [1, 13].

There is no sufficient information on thermo-hydraulic characteristics of such grids [12], and unavailable at all for some grid size. The work [18] presents experimental studies of thermo-hydraulic characteristics of porous-net conic heat transfer elements (mesh: 0.2 mm, wire diameter: 0.13 mm) of rotor heat exchanger with the power of 270 kW applied in transport gas-turbine engines. However, these studies were performed in very narrow temperature range of matrix and heat carriers (in the experiments the net matrix was flushed alternately by air at $T_A = 300$–320 K, and, respectively, the temperature of net matrix T_M varied in the same interval), whereas actually the temperature of air and gas at the inlet of heat exchanger is in the range of 450–490 K and 870–970 K, respectively. A consequence of this fact was significant by 3–4% (absolute) disagreement [1, 13] between experimentally obtained in the mode of matrix temperature in the range of 500–900 K and calculated heat recovery rate of the heat exchanger using empirical dependence of the Colborne factor [12], obtained by experimental data [15]:

$$J_k = 0.11 \cdot Re_x^{-0.46}, \tag{1}$$

where $Re_x = Re \cdot \dfrac{0.00375}{p^3}$ is the modified Reynolds criterion, Re is the Reynolds number, p is the matrix porosity.

In order to determine the verified dependence the thermo-hydraulic processes in porous-net matrix were simulated. The calculated model was a fragment of heat transfer matrix, composed of 10 layers of mesh wire with the step S and wire diameter D (Fig. 1). The mathematical simulation was based on solution of a set of equations including the Navier–Stokes equations. Calculated and theoretical estimations of power characteristics and state of thermo-hydraulic processes were obtained by means of ANSYS CFX software [22]. Thermo-physical properties of air and gas were preset in the form of spreadsheet dependences on temperature [7].

Numerical experiment was performed in the range of Reynolds numbers $Re = 10$–70 (laminar flow). Flushing of matrix by air was performed up to its complete heating or cooling. The temperatures of air T_A and matrix T_M were selected close to their actual values in rotor heat exchanger upon heating $T_A = 965$ K, $T_M = 300$ K and cooling $T_A = 500$ K, $T_M = 965$ K.

As a rule, the Colborne factor is presented as a function only of the Reynolds number $J_k = f(Re_x)$ [9, 16, 29]. In this work the calculated results were processed by the procedure given elsewhere [1, 13].

For each selected time instance the modified Reynolds criterion Re_x and the Colborne factor J_k were determined, as well as the temperature factors for the case of heating Te_{heat} and cooling Te_{cool}, calculated by the temperatures of matrix T_{matr} and air flow at inlet $T_{air\,in}$ and outlet $T_{air\,out}$ of heat exchanger:

$$Te_{heat} = T_{matr}/T_{air\,in}, Te_{cool} = T_{air\,out}/T_{matr}.$$

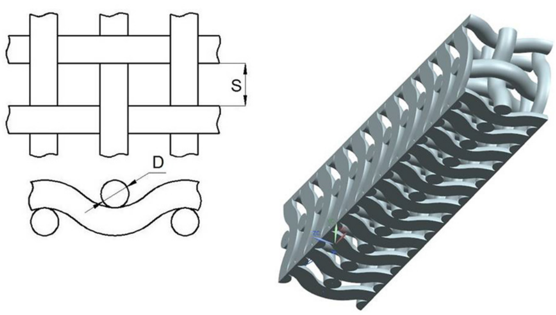

Figure 2: Porous-net matrix: $S = 0.2$ mm, $D = 0.13$ mm.

The parameters Re_x, Te, J_k were determined as follows. For each selected value – $Te = const$ the value pair Re_x, J_k was approximated in the form of polynomial:

$$J_k = A \cdot Re_x^B.$$

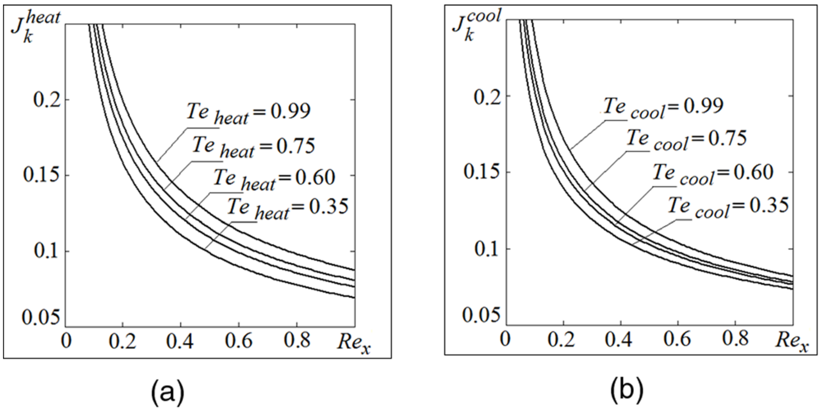

Figure 3: Colborne factors of porous-net matrix upon heating J_k^{heat} (a) and cooling J_k^{cool} (b) as a function of modified Reynolds number for various values of temperature factor Te.

The coefficients A and B were determined by approximating linear dependences on the temperature factor Te.

As a consequence, the dependences of Colborne factors were obtained for various values of temperature factor Te (Fig. 3):

$$\begin{aligned} J_k^{heat} &= (0.036 \cdot Te_{heat} + 0.074) \cdot Re_x^{0.00631 \cdot Te_{heat} - 0.514}, \\ J_k^{cool} &= (0.027 \cdot Te_{\,cool} + 0.091) \cdot Re_x^{-(0.143 \cdot Te_{cool} + 0.32)}. \end{aligned} \tag{2}$$

Equations (2) were verified by simulation of thermo-hydraulic processes using the obtained approximating dependences (1) in porous-net matrix of heat exchanger of a 270 kW transport microturbine (Fig. 1) and comparison of the acquired results with the known experimental data. In rotor heat exchanger the heat transfer elements are located on rotating framework and are flushed alternately by hot and cold heat carriers during operation. It was assumed that the matrix is composed of the mesh wire considered above.

The calculated model was composed of sectors of cylindrical cells of heat exchanger with the circumference of 0.0001m (Fig. 2). Conic heat transfer elements of heat exchangers were mathematically described as porous bodies [22, 24]. Thermo-hydraulic processes upon flowing of gas/air were described by previously obtained dependences for the Colborne factor (2), as well as by dependences of linear and quadratic coefficients of resistance of porous-net matrix [19, 20]:

$$\alpha = \zeta \cdot \frac{p^3 \cdot \mu \cdot Re_x}{0.075 \cdot d^2 \cdot (1 + p \cdot Re_x)},$$

$$\beta = \zeta \cdot \frac{\rho \cdot Re_X}{d \cdot (1 + p \cdot Re_x)},$$

where $\zeta = 0.5k \cdot d \cdot (\frac{1}{Re_x} + 1)$ is the friction factor, $d = 4p/k$ is the hydraulic diameter of matrix channels of heat exchanger, k is the matrix compactness [m^2/m^3], ρ is the air density [kg/m^3].

3. Results and Discussion

The conditions, under which operates heat transfer element of rotating heat exchanger, were simulated by alternate flushing of the calculation model by gas and air in one calculation cycle (see Fig. 4). The alternate flushing of heat exchanger cell by gas and air was performed until obtaining of steady mode. Such mode corresponded to variation not exceeding 1% of amount of heat transferred from gas to air in two adjacent rotations.

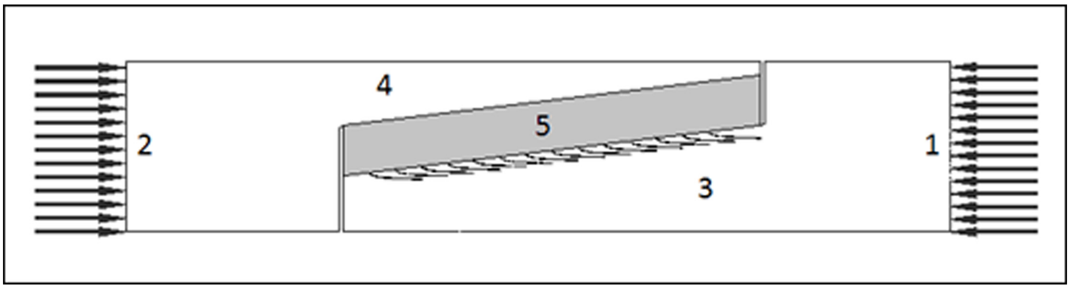

Figure 4: Calculation model of conic porous-net element of rotor heat exchanger (flat cross section): 1 – gas inlet (air outlet), 2 – gas outlet (air inlet), 3 – gas inlet duct, 4 – air inlet duct, 5 – heat transfer matrix with guiding grid.

The following data were used in the calculations: heat exchanger rotation frequency $n = 24\,\mathrm{min}^{-1}$; gas (air) flow rate across the simulated matrix $G = 1.334 \cdot 10^{-5}$ kg/s (corresponds to gas or air flow rate across overall heat exchanger $G_\Sigma = 2$ kg/s); the temperature of gas $T_{gas} = 965$ K and air $T_{air} = 470$ K at heat exchanger inlet; the pressure of gas $P_{gas} = 101325$ Pa and air $P_{air} = 395167$ Pa at heat exchanger inlet.

As a consequence of numerical simulation the distributions of pressure and temperature in heat transfer matrix of heat exchanger package were obtained (Figs. 5, 6), as well as pressure drops in heat exchanger and temperatures of gas and air at the outlet of rotor heat exchanger at any time of its rotation.

The heat recovery rates σ and hydraulic resistance ΔP of heat exchanger were determined by the equations:

$$\sigma = \frac{T_{mid} - T_{air}}{T_{gas} - T_{air}}, \tag{3}$$

$$\Delta P = \frac{\sum_i (P_i \cdot \Delta t)}{t}, \tag{4}$$

where $T_{mid} = \frac{\sum_i (T_i \cdot \Delta t)}{t}$ is the average integral air temperature at heat exchanger outlet in half of the time of its rotation; i is the number of current time increment; T_i is the air temperature at heat exchanger outlet at the i-th time step; Δt is the value of time step; t is the half time of rotation of heat exchanger.

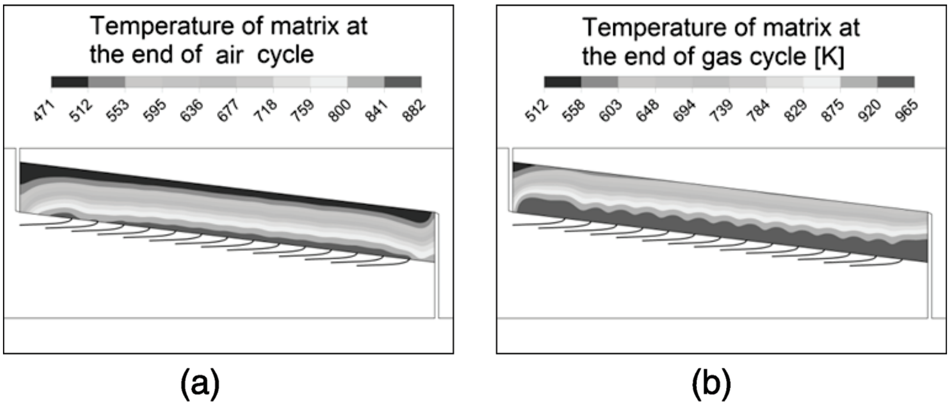

Figure 5: Temperature distribution in matrix in steady mode at the end of purging by air (a) and gas (b).

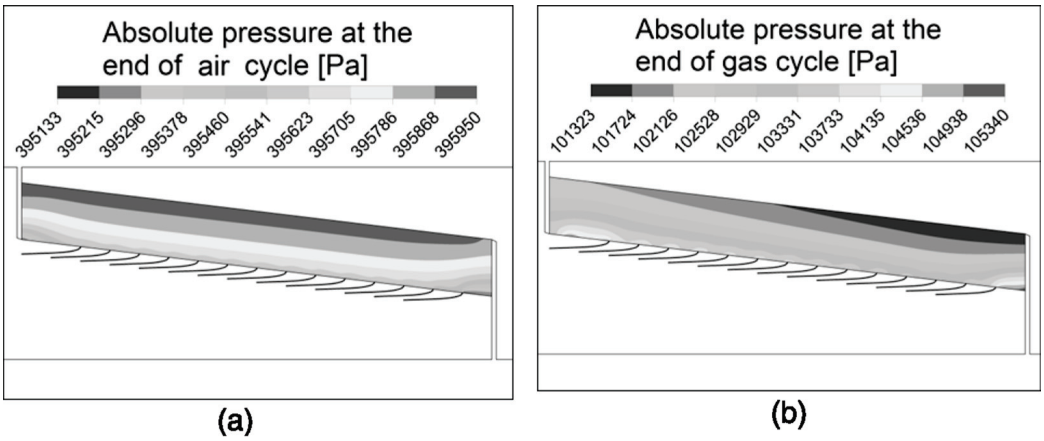

Figure 6: Pressure distribution in matrix in steady mode at the end of purging by air (a) and gas (b).

Table 1 summarizes the calculated characteristics of thermo-hydraulic processes in rotor heat exchanger with conic porous-net heat transfer elements in comparison with experimental data. The data in the Table evidence that the calculated characteristics of simulated thermo-hydraulic process on the basis of the obtained Eq. 1 for the Colborne factor provide closer (by 1.5%) agreement with the data of full-scale experiment [18].

Table 1: Calculated and experimental values of heat recovery rate σ and pressure loss with gas ΔP_{gas} and air ΔP_{air} of rotor heat exchanger with conic porous-net heat transfer elements of a 270 kW microturbine.

	Calculations in the basis of		Experimental studies of full-scale specimen of rotor heat exchanger [18].
	empirical Eq. (1) [15].	verified dependences of Colborne factor (2).	
ΔP_{gas} , Pa	3950	4130	4080
ΔP_{air}, Pa	910	990	980
σ, %	86	83,5	84

4. Conclusions

1. Thermo-hydraulic processes have been simulated in porous-net matrix composed of 10 layers of metallic mesh wire used in heat transfer elements of rotor heat exchangers of low-powered microturbines.

2. The dependences of Colborne factors have been verified, which describe heat transfer upon heating and cooling of net heat transfer matrix of rotor heat exchanger of traction microturbines.

3. The calculated results of simulated thermo-hydraulic process in rotor heat exchanger of a 270 kW microturbine based on the temperature dependences for Colborne factor are in good agreement with the experimental data in the range of one and a half percent.

Acknowledgments

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References

[1] Alekseev R.A., Kostyukov A.V., and Kosach L. A. (2012). Investigation of heat transfer process in the net matrix of rotary heat exchanger, *Izvestiya MGTU "MAMI"* [Bull. of Moscow State University of Mechanical Engineering (MAMI)], no. 2(14), pp. 19-22 (in Russ.).

[2] Borozdina O.Yu., Eliseeva I.I., Mertins K., and Rittigkhauzen Kh. (2012). National strategies for nuclear and wind energy in Germany and Russia. *Finansy i biznes* [Finance and business], no. 3, pp. 30–39 (in Russ.).

[3] Bowman Power Systems. (2016). UK. Retrieved April 04, 2016, from http://www.bowmanpower.com

[4] BP Statistical Review of World Energy. (2015). UK. Retrieved April 04, 2016, from http://www.bp.com/ statisticalreview

[5] Capstone Turbine Corporation (2016). USA. Retrieved April 04, 2016, from http://www.capstoneturbine.com

[6] Capstone Turbine Corporation. (2015). *Combined Heat and Power Systems Technology Development and Demonstration 370 kW High Efficiency Microturbine*. Los Angeles, CA (United States). DOE Project ID # DE-EE0004258. 2015-10-14. Technical Report, p. 187. DOI: 10.2172/1224801.

[7] Eliseev S.Yu. (2005). *Theoretical basis and implementation methods to improve characteristics of transport regenerative gas turbine engines*. (Doctoral dissertation). Moscow, University of Mechanical Engineering (MAMI) (in Russ.).

[8] Elliott Energy Systems Inc. Calnetix Power Solutions. (2016). USA. Retrieved April 04, 2016, from http://www. elliott-turbo.com; www.calnetix.com

[9] Heidari-Kaydan, A., and Hajidavallo, E. (2014). Three-dimensional simulation of rotary air preheater in steam power plant, *Applied Thermal Engineering*, vol. 73, pp. 397–405.

[10] Honeywell. *Honeywell Power Systems*. (2016). Retrieved April 04, 2016, from http://www.honeywell.com

[11] Ingersoll Rand. *Ingersoll Rand Energy Systems.* Ireland. Retrieved April 04, 2016, from http://www.ingersollrandproducts.com; www.ingersollrand.com

[12] Kays W. M., & London A. L. (1964). *Compact heat exchangers*. (2nd ed.). McGraw-Hill Series in Mechanical Engineering. New York, 1964. 272 p.

[13] Kostykov A., Makarov A., Alexeev R., and Merzlikin V. (2012). The structured rotor-type heat exchange for microturbines. *FISITA 2012 World Automotive congress. 27th – 30th November 2012. "Proceedings and Abstracts", Paper Reference Number F2012-A07-025*, pp. 78–79. Beijing, China.

[14] Krass M.S. (2012). Electric-power industry in the Russian economy. *EKO* [EKO], no. 7, pp. 136–150 (in Russ.).

[15] Lebed' N.N. (1971). Study of hydraulic and heat transfer characteristics of the heat transfer surfaces for the rotating section type regenerator. Nikolaev Shipbuilding Inst. named after Admiral S.O. Makarov, Nikolaev. Scientific and Technical Report. Russia (in Russ.).

[16] Mioralli, P.C., and Ganzarolli, M.M. (2013). Thermal analysis of a rotary regenerator with fixed pressure drop or fixed pumping power. *Appl. Therm. Eng.*, vol. 52, pp. 187–197.

[17] Nissan Motor Company (2016). Rotary regenerator. Japan. Retrieved April 04, 2016, from http://www.toyota.co.jp

[18] Plotnikov D.A. (1981). Development and research of the structural rotary regenerators of gas turbine engine. (Doctoral dissertation). Moscow, University of Mechanical Engineering (MAMI) (in Russ.).

[19] Popov I.A. (1996). Study of flow and heat exchange in channel with high-porous cellular materials for forced convection of single-phase and boiling working fluid. *Proc. of Int. Conf. on Porous Media and it's Applications in Science, Engineering and Industry.* Kona, Hawaii, USA.

[20] Popov I.A. (1997). The study of hydrodynamics and heat transfer in channels heat exchangers based on highly porous materials. *Proc. of Int. Conf. "Compact heat exchangers for industry".* Snowbird. Publishing House Bejel House Inc., USA.

[21] Report on the Functioning of Unified Electric Power System (UEPS) of Russia in 2015 (in Russ.). Retrieved April 04, 2016, from http://www.so-ups.ru

[22] Software "ANSYS CFX 2014". Theory Guide. ANSYS Inc.

[23] Turbec S.p.A. *Company Overview*. Italy. Retrieved April 04, 2016, from http://investing.businessweek.com/Research/stocks/private/snapshot.asp?privcapId=8170375

[24] Wei, X. J., Joshi, Y. K., and Ligrani, P. M. (2007). Numerical Simulation of Laminar Flow and Heat Transfer Inside a MicroChannel With One Dimpled Surface. *J. of Electronic Packaging,* vol. 129, iss.1, pp. 63–70.

[25] Wilson, D.G., and Korakianitis, T.P. (1998). The design of high-efficiency turbomachinery and gas turbines. Second edition. Prentice-Hall, Upper Saddle River, NJ.

[26] Wilson, D. G., and Pfahnl, A.C. (1997). A look at the automotive-turbine regenerator system and proposals to improve performance and reduce cost. *SAE Paper 9270237.* Warrendale, PA.

[27] Wilson, D.G. (2010). The high efficiency of our multistage ceramic-bladed turbine design can produce an attractive economic return even in the absence of CHP. Wilson TurboPower Inc. Wilson Solarpower Corporation.

[28] Wilson D.G. (2002.) The basis for the prediction of high thermal efficiency in WTPI gas-turbine engines, Wilson TurboPower Inc.

[29] Wu, Z., Melnik, R.V.N., and Borup F. (2003). Model-based analysis and simulation of regenerative heat. MCI technical report, University of Southern Denmark. 26 p.