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Computational and Experimental Study of Thermal Hydraulic Properties of Slotted Matrix of Rotary Regenerator

Andrey Veniaminovich Kostyukov, Givi Guramovich Nadareishvili, Lev Anatolyevich Kosach

***Abstract*: This article discusses thermal properties of slotted heat transfer matrix of rotary regenerators of small scale gas turbine engines (microturbines). Thermal processes in channels of slotted matrix of rotary regenerator have been predicted, the model of rotary regenerator with slotted heat transfer matrix has been analyzed. The predictions were based on finite volume software, the experiments were carried out on test rig with the regenerator model. Distribution of Nusselt criterion along the channel length as well as stabilized Nusselt criterion are presented. The influence of velocity, sizes, and temperature on stabilized Nusselt criterion has been studied. Experimental and predicted regeneration rates of rotary regenerator with slotted heat transfer matrix are given, their close correlation has been obtained.**

***Index Terms*: heat exchange, microturbine, regenerator, convection, Nusselt number, experiment.**

I. INTRODUCTION

Gas turbine appliances of moderate power (microturbines) are widely applied [1]. A promising trend of development of microturbine market is distributed power generation due to their small sizes, possibility of rapid start, reliability, long lifetime, environmental safety [2, 3]. Another promising trend is application of microturbine as a component of hybrid power generating assembly. Nowadays hybrid assemblies with reciprocating engines as power generators are widely applied [4, 5, 6].

Improvement of microturbine competitiveness assumes significant increase in their efficiency. One of the main approaches to efficiency improvement of existing microturbines is increase in regeneration rate of their heat exchangers [7]. In particular, in rotary regenerators it is possible to increase regeneration rate up to 95%, which will provide competitiveness of microturbines in terms of fuel efficiency comparable with the best reciprocating ICE. Flow pattern in such regenerators is deeply laminar. The most promising for these regimes is slotted heat transfer matrix due to high Nusselt number upon flows with small Reynolds numbers.

Procedure of thermal hydraulic development of rotary regenerator with slotted matrix [8] assumes presetting of thermal properties of heat transfer matrix of regenerator, more exactly: Nusselt numbers. For the case of constant temperature of slot walls the solution is available [9] according to which the minimum Nusselt criterion in this channel is 7.62. In actual regenerator this condition is obviously not satisfied: slot wall temperature is not constant, hence the obtained minimum Nusselt criterion should be verified.

II. METHODS

The problem with the condition of varying temperature of slot wall cannot be solved analytically. In this work gas flow was simulated with subsequent determination of Nusselt criterion using computational method. In addition, the influence of temperature, velocity, and sizes on Nusselt criterion for slot channel was analyzed.

In order to verify correctness of formulation of the problem for computational solution, approbation was carried out by means of solution of simulation problem of thermal hydraulic processes in flat slot with constant temperature of its wall.

Computational model of regenerator slotted matrix was comprised of: one half (along the height) of slot and one half of the thickness of slot steel wall, inlet and outlet segments with the length of 20 mm in order to account for phenomena occurring upon air inflow and outflow from slot channel. The length of the considered slot channel was 96 mm.

Computations were performed at various Reynolds numbers (from 30 to 1,677) at inlet to flat slot with variations of slot width (0.4 mm and 0.7 mm) and air flow rates at slot inlet.

At the model inlet, excessive pressure was preset: 8,600 Pa, at the wall: constant temperature of 403 K, at other model boundaries: symmetry conditions.

In order to estimate the obtained results as well as computation shown below, the considered channel was separated by transversal cross section into minor segments for which Nusselt criterion was determined:

$$Nu = \frac{\alpha*2*\Delta}{\lambda} \quad (1)$$

where Nu was the Nusselt criterion at the considered segment, Δ was the height of slot channel, λ was the average coefficient of heat conductance at the considered segment, α was the average coefficient of heat release at the considered segment:

$$\alpha = \frac{Q}{F*dT} \quad (2)$$

where F was the wall surface area at the considered

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Andrey Veniaminovich Kostyukov, NAMI Russian State Scientific Research Center, Moscow, Russia.

Givi Guramovich Nadareishvili, NAMI Russian State Scientific Research Center, Moscow, Russia.

Lev Anatolyevich Kosach, Moscow Polytechnic University, Moscow, Russia.

segment, dT was the difference of average temperature of wall and gas at the considered segment:

$$dT = \frac{T_{W1}+T_{W2}}{2} - \frac{T_1+T_2}{2} \quad (3)$$

Q was the thermal flow at the considered segment,

$$Q = C_p * G * (T_2 - T_1) \quad (4)$$

where T_1 was the average air temperature at inlet to the considered segment, T_2 was the average air temperature at outlet from the considered segment, T_{W1} was the average wall temperature at inlet to the considered segment, T_{W2} was the average wall temperature at outlet from the considered segment, G was the air mass flow rate, C_p was the average air heat capacity at the considered segment.

The channel of slotted matrix of actual regenerator in addition to walls also includes supporting hemispheres providing the required slot size. Aiming at verification of possible simplification of the computational model (elimination of the supporting hemispheres), comparative analysis of two channel variants was performed earlier: a) with the supporting hemispheres, b) without the hemispheres.

Verification was performed upon stationary flow of air ("gas") in the slot. Temperature distribution along the plate length was taken from the previous nonstationary computations (the last time increment) [10].

Analysis of the obtained results demonstrated that the use of simplified geometry led to relatively insignificant decrease in Nusselt numbers (3.6%) together with significant decrease in computation time, therefore, heat exchange in slots with varying wall temperature was computed using simplified model without supporting hemispheres.

The performed computations [10] demonstrated that the temperature distribution along the slot wall length in matrix rotary regenerator of microturbine was close to linear, therefore, the next computation stage was performed with linear temperature distribution along the slot wall length.

The influence of temperature on Nusselt criteria was exemplified by three cases: a) air inlet temperature: 288 K, linear variation of temperature along the slot wall length from 300 to 383 K; b) air inlet temperature: 288 K, linear variation of temperature along the slot wall length from 503 to 923 K; c) air inlet temperature: 483 K, linear variation of temperature along the slot wall length from 503 to 923 K.

In addition, as for the case with constant temperature of slot channel wall, the influence of size and velocity was analyzed.

The obtained results were verified by means of experimental studies of air flow in slotted heat transfer matrix of regenerator.

The experimental study was carried out on the model of rotary regenerator with slotted matrix in the form of rectangular packages fabricated of steel bands with supporting hemispheres.

Geometrical properties of heat transfer matrix of rotary regenerator are as follows:

– slot length: 96 mm;
– slot width: 0.4 mm;
– thickness of steel band: 0.1 mm.

The experimental facility is illustrated schematically in Fig. 1.

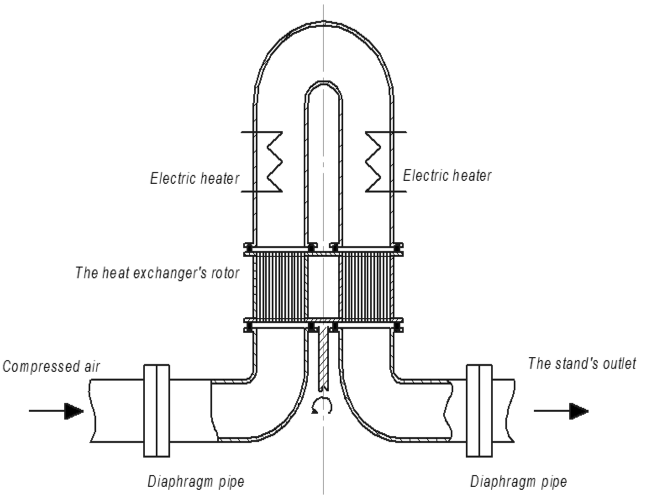


Fig. 1. Schematic view of experimental facility.

Air was supplied to the regenerator using piston compressor.

External heating of air was carried out by electrical heaters. Air after passing via external electric heater was referred to as "gas".

Rotary regenerator was activated by DC motor connected with the regenerator by worm reducer.

Mass flow rates of heat carriers at inlet and outlet were measured by means of orifices.

The temperatures of air and "gas" at regenerator inlet and outlet were measured by two quick response thermocouples installed on rotary disc (copper–constantan, diameter: 0.07 mm) for continuous temperature monitoring (Fig. 2).

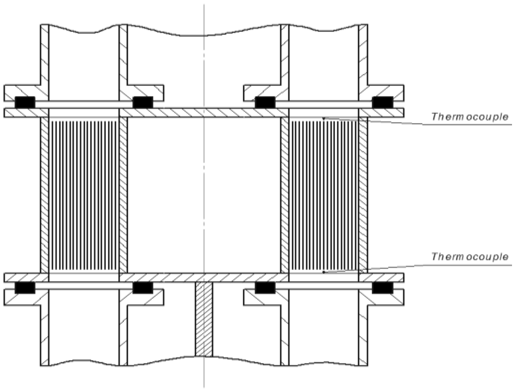


Fig. 2. Positions of quick response thermocouples.

The applied thermocouples were calibrated using reference platinum rhodium thermocouple.

Signal from the thermocouples was transferred to data acquisition unit rotating together with the regenerator, and then via Wi-Fi connection to personal computer.

The experimental studies were carried out under the following conditions:

– air and "gas" flow rates via the regenerator: 7.6 g/s;
– air and "gas" temperature at the regenerator inlet: 127°C and 26°C, respectively;
– regenerator rotation frequency: 15 rpm.

Experimental results were presented in the form of oscillograms of air temperature at regenerator inlet and "gas" temperature at regenerator outlet, as well as air temperature at regenerator outlet and "gas" temperature at regenerator inlet.

The obtained oscillogram was processed as follows: average temperatures of heat carriers (air, "gas") at regenerator inlet and outlet were determined as follows:

$$\overline{\overline{T}} = \left(\sum_{i=0}^{n} T_i * \Delta t_i\right)/t \quad (5)$$

where $\overline{\overline{T}}$ was the average temperature, K, T_i was the temperature upon the i-th measurement, K, Δt_i was the i-the time increment, s, t was the time of measurements, s, n was the number of time increments during overall time of measurements.

Then the obtained temperature values were used for determination of regeneration rate of rotary regenerator as follows:

$$\sigma = \frac{T_{g\_in} - T_{g\_out}}{T_{a\ in} - T_{x\ in}} \quad (6)$$

where $T_{x\ in}$ was the air temperature at regenerator inlet, K, $T_{a\ in}$ was the "gas" temperature at regenerator inlet, K, $T_{a\ \ out}$ was the "gas" temperature at regenerator outlet, K.

In order to confirm Nusselt criteria in slot channels of regenerator obtained by mathematical simulation (Fig. 2-4), thermal hydraulic analysis of rotary regenerator with slotted matrix was performed according to the procedure in [8] using the adjusted Nusselt criterion (10).

III. RESULTS

Figure 3 illustrates the predicted distribution of Nusselt criterion along the length of slot channel with steady temperature of its wall at the slot width of 0.4 mm, wall temperature: 403 K, air temperature at channel inlet: 288 K, Reynolds number at channel inlet: 300.

The influence of slot width and Reynolds numbers on the curve form is constrained only by short inlet segment. In addition, the slot width and Reynolds numbers do not exert influence on minimum Nusselt numbers in the slot.

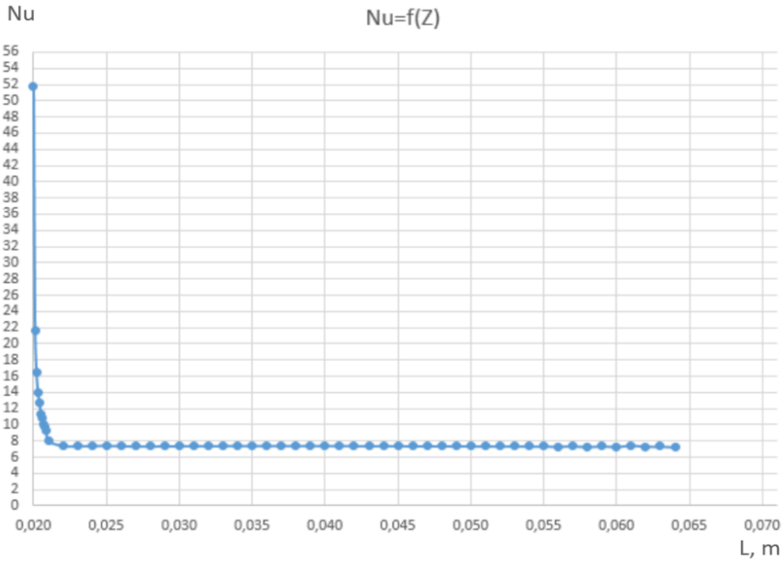


Fig. 3. Distribution of Nusselt criterion along the channel length at constant temperature of slot walls (slot width: 0.4 mm, constant temperature: 403 K, air temperature at channel inlet: 288 K, Reynolds number at channel inlet: 300).

Figure 4 illustrates the predicted distribution of Nusselt criterion along the length of slot channel with linear temperature distribution along the wall length from 503 to 923 K upon slot width of 0.4 mm, air temperature at channel inlet: 288 K, Reynolds number at channel inlet: 292.

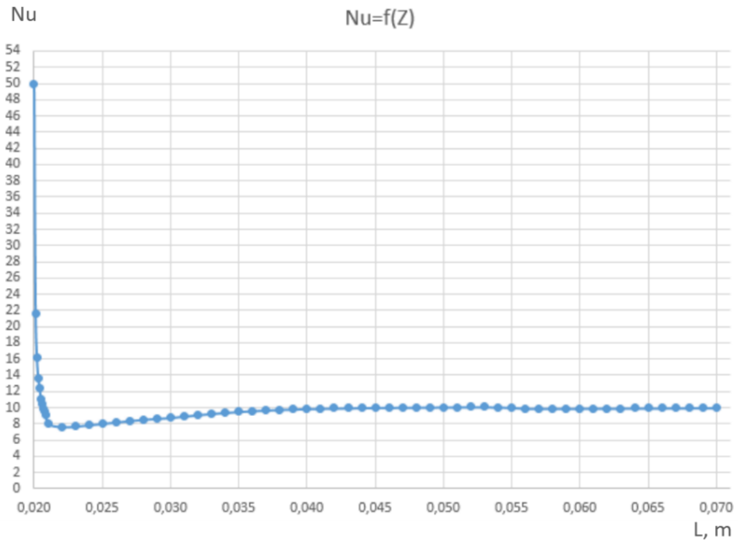


Fig. 4. Distribution of Nusselt criterion along the channel length at varying temperature of slot walls (slot width: 0.4 mm, linear distribution of wall temperature: from 503 to 923 K, air temperature at channel inlet: 288 K, Reynolds number at channel inlet: 292).

Tables 1, 2 and Figs. 5, 6 present studies of the influence of temperature, velocity, and sizes on stabilized Nusselt criterion

Table 1. Stabilized Nusselt criterion as a function of temperature (slot width: 0.4 mm)

Reynolds number at channel inlet	Air temperature at channel inlet, °C	Wall temperature at slot inlet, °C	Wall temperature at slot outlet, °C	Nusselt criterion
205	288	300	383	10.046
211	288	503	923	9.991
216	483	503	923	10.013

Table 2. Stabilized Nusselt criterion as a function of velocity (slot width: 0.4 mm, linear distribution of wall temperature: from 503 to 923 K, air temperature at channel inlet: 288 K)

Reynolds number at channel inlet	34	92	151	211	272	333	394	599	805	1,011
Nusselt criterion	10.028	10.032	9.956	10.072	10.055	9.974	10.008	9.953	10.035	10.021

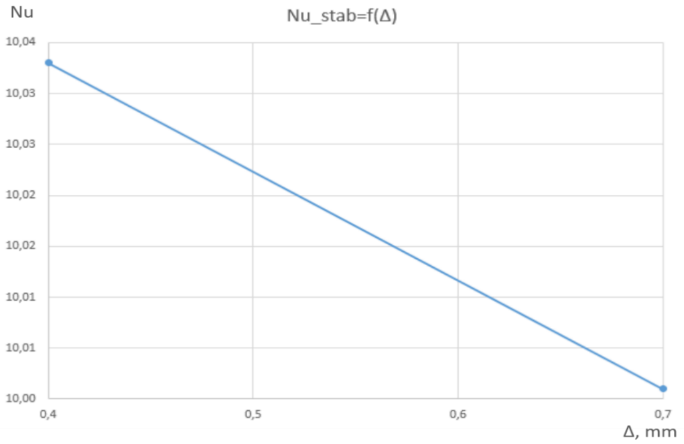


Fig. 5. Stabilized Nusselt criterion as a function of size (linear distribution of wall temperature: from 503 to 923 K, air temperature at channel inlet: 288 K).

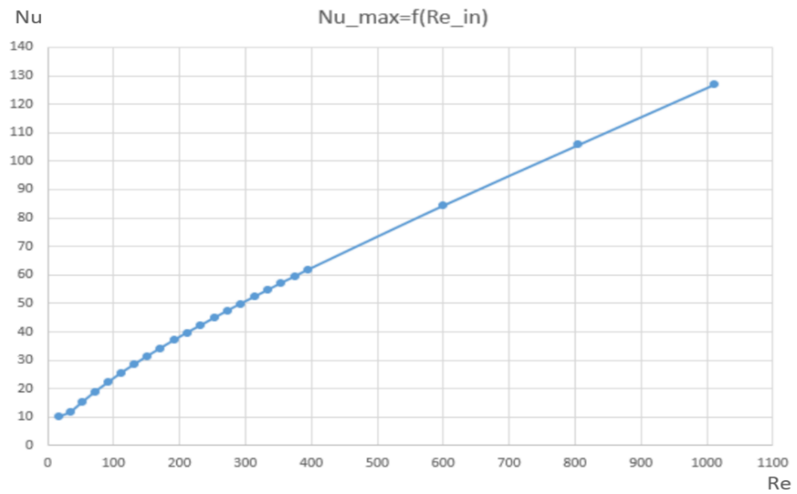
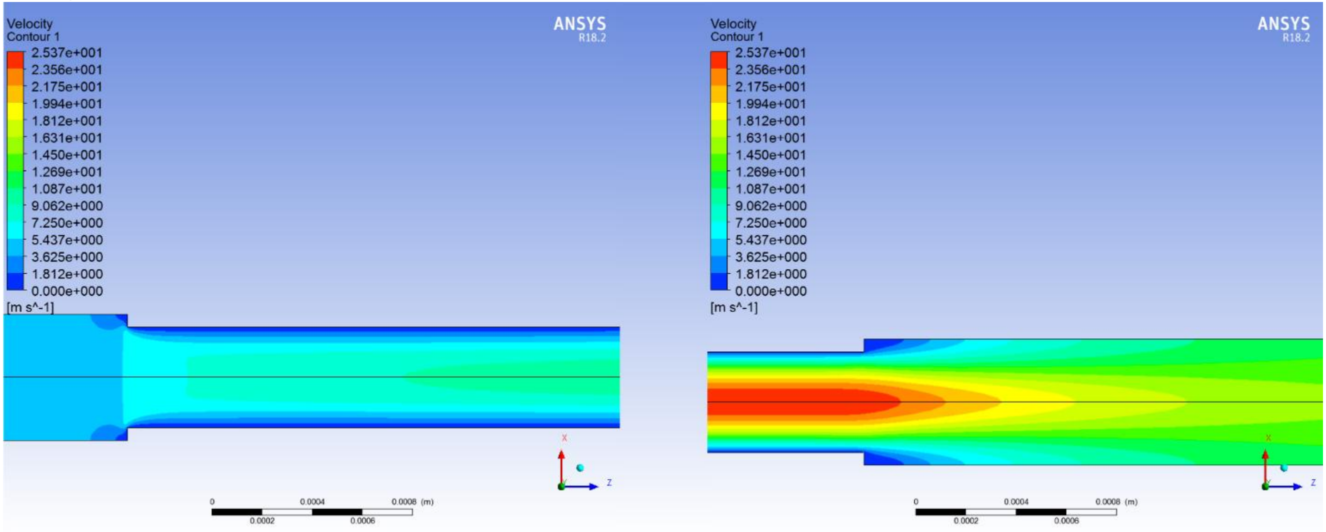


Fig. 6. Maximum Nusselt criterion as a function of Reynolds number at channel inlet (slot width: 0.4 mm, linear distribution of wall temperature: from 503 to 923 K, air temperature at channel inlet: 288 K).

Figure 7 illustrates the predicted distribution of flow velocity in the slot.



a) slot inlet b) slot outlet

Fig. 7. Velocity field in longitudinal cross section of slot channel (slot width: 0.4 mm, linear distribution of wall temperature: from 503 to 923 K, air temperature at channel inlet: 288 K, Reynolds number at channel inlet: 292).

Experimental oscillograms of temperatures of air entering into regenerator and "gas" escaping from it (curve 1) and temperatures of air escaping from regenerator and "gas" entering into it are illustrated in Fig. 8.

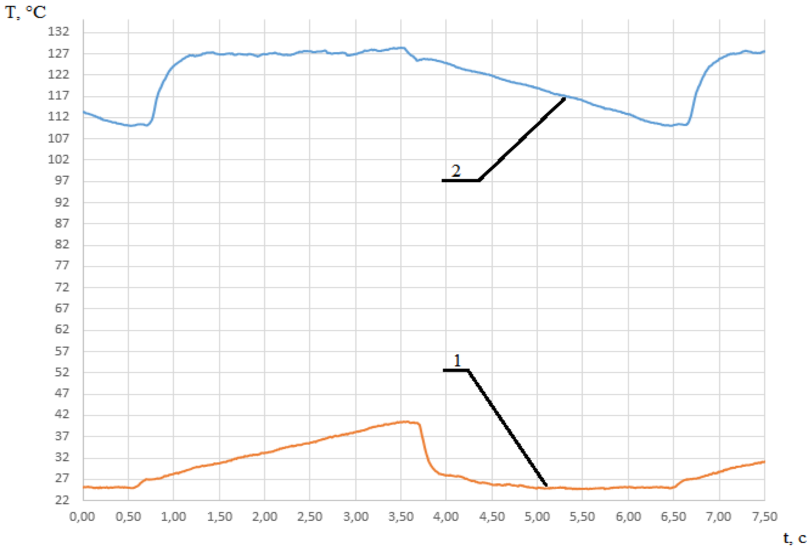


Fig. 8. Temperature of heat carrier as a function of time.

Results of experimental data processing according to the above-mentioned procedure are summarized in Table 3.

Table 3. Experimental data after processing

Averaged air temperature at regenerator inlet, K	26.0
Averaged "gas" temperature at regenerator inlet, K	127.1
Averaged "gas" temperature at regenerator outlet, K	34.4
Regeneration rate, %	91.7
Reynolds number range	188-235

Predictions according to the procedure [8] using initial and adjusted Nusselt criterion provided regeneration rate of 89.4% and 91.4%, respectively.

IV. DISCUSSION

It can be seen in Fig. 3 that the obtained minimum Nusselt criterion in slot channel with constant wall temperature is 7.43, which is very close to the Nusselt criterion obtained for this case analytically (7.62). Therefore, it is possible to conclude that the developed complex for simulation of thermal hydraulic processes in slot channels upon laminar gas flows was successfully verified.

Analysis of predictions in the case of varying wall temperature revealed that the form of distribution of Nusselt criterion along the channel length varied with respect to that obtained for constant temperature of slot wall (Fig. 4). It can be seen that under such conditions the Nusselt criterion decreases to its minimum at initial segment and then increases reaching steady value equaling to 10.

Analysis of the influence of temperature, velocity, and sizes on stabilized Nusselt criterion demonstrated that under such conditions it did not depend on such factors. Tables 1, 2 and Figs. 5, 6 show that variation of temperature regime, variation of air mass flow rate, and variation of slot size actually did not vary stabilized Nusselt criterion.

The velocity factor exerts influence on the form of distribution of Nusselt criterion along the channel length: with the increase in the Reynolds number at channel inlet, the minimum Nusselt criterion increases up to the extent that at high Reynolds number the curve inflection disappears, and, as a consequence, the minimum and stabilized Nusselt criteria become equal. The temperature and size factors also exert influence on the form of this curve: with the increase in the wall temperature and the temperature of inlet air as well as with the increase in slot size, the curve inflection disappears at lower Reynolds number.

In addition, the velocity factor also contributes significant influence on maximum Nusselt criterion observed at the channel tip, however, since Nusselt criterion rapidly drops in relatively small area, this fact does not lead to any significant influence on heat exchange efficiency in slot channel.

Predictions according to the procedure [8] demonstrated that application of the adjusted Nusselt criterion (10) for slotted matrix provided the regeneration rate of 91.4% which was very close to the experimental value (91.7%), whereas with the Nusselt number of 7.62, the regeneration rate was 89.4%.

V.CONCLUSION

1. Finite volume method has been verified for simulation of thermal hydraulic processes in slot channel upon laminar gas flow. Correlation has been obtained between the calculated Nusselt criterion and that published in [9] for gas flow in slot channel at constant wall temperature.
2. Distribution of Nusselt criterion along the length of slot channel with varying temperature of walls has been determined. The obtained stabilized Nusselt criterion in slot significantly exceeds the respective value obtained at constant temperature of slot wall equaling to 10.
3. It has been demonstrated that in the case of varying temperature, the Nusselt criterion at slot inlet at first sharply drops to minimum (7.6) and then increases at small segment achieving maximum 10 and then remains steady, the length of this segment increases with the increase in the Reynolds number at channel inlet.
4. Thermal hydraulic properties of slotted matrix of rotary regenerator have been

experimentally studied, regeneration rate equals to 91.7%.

5. It would be reasonable to apply adjusted Nusselt criterion (10) upon prediction of thermal efficiency of rotary regenerators with slotted matrices.

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