Regenerator heat exchanger – calculation of heat recovery efficiency and pressure loss

Different configuration sensitivity analysis

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Introduction

Performance of heat exchangers is determined based on two main parameters: efficiency to exchange / recover heat and pressure loss due to friction between fluid and exchanger surfaces.
These two parameters are contradicting each other which mean that the higher is efficiency the higher becomes pressure loss. The aim of the optimized design of heat exchanger is to reach the highest or the required heat efficiency and at the same time to keep pressure losses as low as possible keeping total exchanger size within acceptable size.
In this report is presented analytical calculation method to calculate efficiency and pressure loss in the regenerator heat exchanger with a fixed matrix that will be used in the decentralized ventilation unit combined in the roof window. Moreover, this study presents sensitivity study of regenerator heat exchanger performance, taking into account, such parameters as: geometry, matrix material, surface geometry, shifting time, air flow.

Theoretical background

Regenerator effectiveness

Theoretical background presented in this report is also broader elaborated in [1].

Regenerator effectiveness is a function of four dimensionless numbers as presented below:

$$\varepsilon = \phi[NTU_0, C^*, C_r^*, (hA)^*]$$

Where dimensionless numbers can be presented as follows:

$$NTU_0 = \frac{1}{C_{min}}\left[\frac{1}{1/(hA)_h + 1/(hA)_c}\right]$$

$$C^* = \frac{C_{min}}{C_{max}}$$

$$C_r^* = \frac{C_r}{C_{min}}$$

$$(hA)^* = \frac{(hA) on\ the\ C_{min} side}{(hA) on\ the\ C_{max} side}$$

Matrix wall heat capacity rate Cr for a fixed-matrix or rotary regenerator is defined as follows:

$$C_r = \begin{cases} M_w C_w N = \overline{C_r} N & rotary\ regenerator \\ \frac{M_w C_w}{P_t} = \frac{\overline{C_r}}{P_t} & fixed - matrix\ regenerator \end{cases}$$

In this study case both fluid flows have equal capacity ratio (inlet and outlet air volume flow and type of gas is the same).

Knowing *C** and *NTUo* the counter-flow regenerator effectiveness Ɛcf can be determined from:

$$\varepsilon_{cf} = \frac{1 - \exp[-NTU_0(1 - C^*)]}{1 - C^* \exp[-NTU_0(1 - C^*)]} \xrightarrow[C^*=1]{} \frac{NTU_0}{1 + NTU_0}$$

Knowing *Cr** and *Ɛcf*, the regenerator effectiveness Ɛ can be calculated from (**valid for ε<0,9**):

$$\varepsilon = \varepsilon_{cf}[1 - \frac{1}{9(C_r^*)^{1.93}}]$$

Longitudinal wall heat conduction effect on regenerator effectiveness

This parameter might be not negligible, particularly for a high effectiveness regenerators having short flow length *L*. Longitudinal wall conduction reduces the exchanger effectiveness. One side of regenerator is always hotter than the other. Hence, longitudinal heat conduction in the matrix wall occurs in the same direction through both periods. Effect of longitudinal wall heat conductivity adds to the governing differential equation dimensionless number λ, where:

$$\lambda = \frac{k_w A_{k,t}}{L C_{min}}$$

And k_w - is matrix thermal conductivity, $A_{k,t}$ – is section area of the matrix, L is matrix depth.
Including longitudinal wall heat conduction in efficiency calculation is obtained by using following expression:

$$\varepsilon = \varepsilon_{cf}\left[1 - \frac{1}{9(C_r^*)^{1.93}}\right](1 - \frac{C_\lambda}{2 - C^*})$$

where

$$C_\lambda = \frac{1}{1 + NTU_0(1 + \lambda\Phi)/(1 + \lambda NTU_0)} - \frac{1}{1 + NTU_0}$$

Pressure drop calculation

Total pressure loss on the heat exchanger is described by following equation:

$$\frac{\Delta p}{p_i} = \frac{G^2}{2 g_c \rho_i p_i}\left[\underbrace{1 - \sigma^2 + K_c}_{entrance\ effect} + \underbrace{2\left(\frac{\rho_i}{\rho_0} - 1\right)}_{momentum\ effect} + \underbrace{f\frac{L}{r_h}\rho_i\left(\frac{1}{\rho}\right)_m}_{core\ friction} - \underbrace{(1 - \sigma^2 - K_e)\frac{\rho_i}{\rho_0}}_{exit\ effect}\right]$$

Normally core frictional pressure is dominating term. Normally the core pressure drop represents 90 % or more of total pressure drop for gas flows in many compact heat exchangers. The entrance effect represents the pressure loss, and the exit effect represents in many cases a pressure rise.

Prototype regenerator heat exchanger

Prototype regenerator heat exchanger is presented in Fig. 1, however also other configurations and geometries are considered in this study. The prototype is a flat plate regenerator made of high density polystyrene (HDP), see the prototype in Fig. 1.

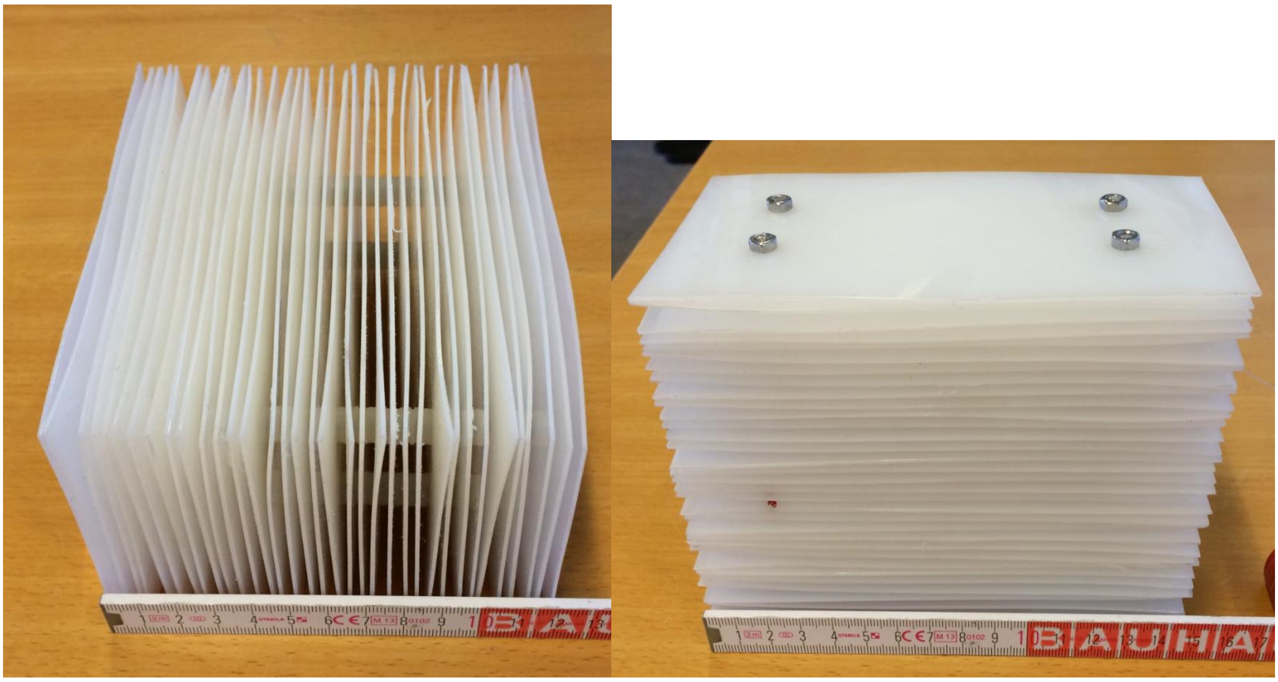


Fig 1. Prototype of flat plate regenerative heat exchanger.

Following parameters are considered in the initial study of the prototype exchanger:

GEOMETRY
Length: 18 cm
Width: 2 x 12 =24 cm
Height: 8 cm
Plate thickness: 1 mm
Number of plates 70

AIR FLOWs:
Volume flow (filter G3): 20,5 [m³/h]
Volume flow (filter G2): 22 [m³/h]
Volume flow (no filter): 25,2 [m³/h]

HEAT EXCHANGER MATERIAL PROPERTIES:
Density: 930 [kg/m³]
Thermal conductivity: 0,5 [W/mK]
Specific heat capacity: 1900 [J/kgK]

OTHER:
Shifting time (total shifting time): 70 [s]

Results – prototype heat exchanger

Using analytical effectiveness and pressure loss calculation method presented in [1] and in the first chapter of this report following results are obtained as presented in Fig. 2.

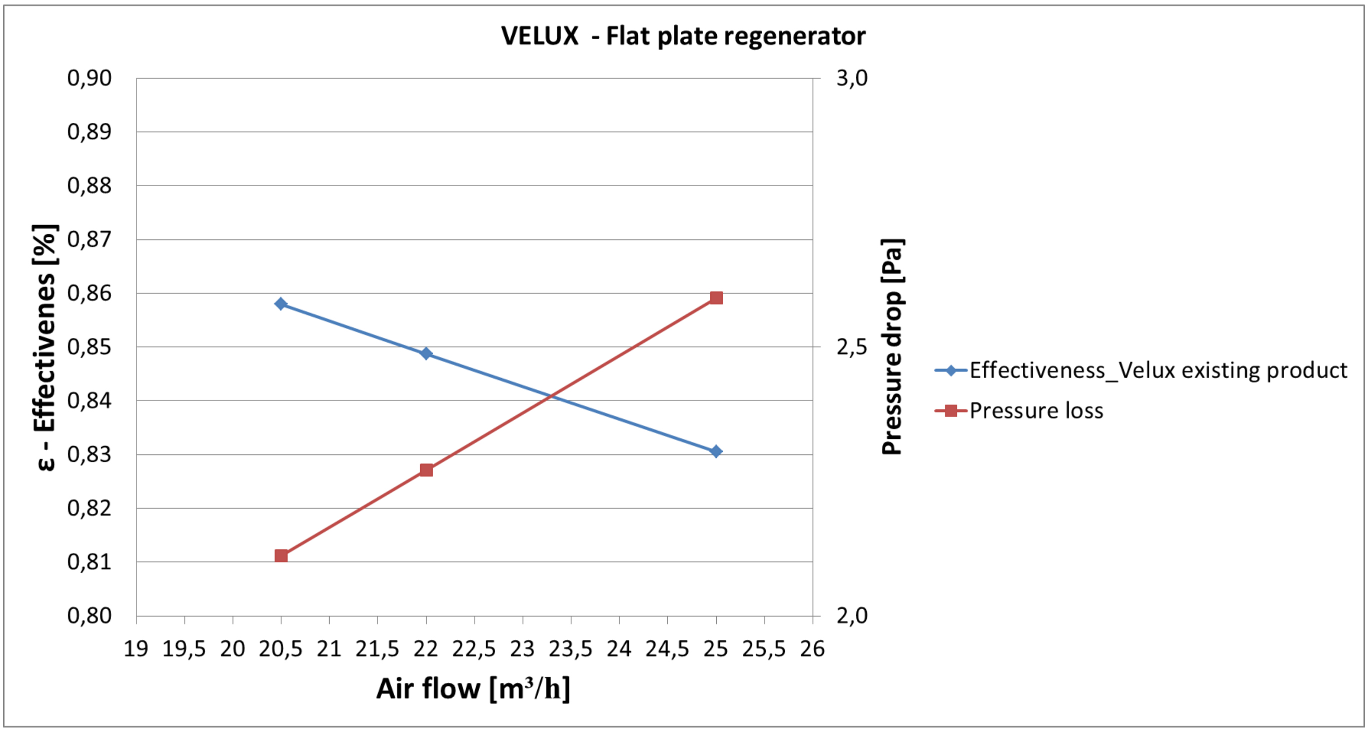


Fig 2. Effectiveness and pressure loss calculated for existing flat plate regenerator exchanger.

Pressure loos fraction for regenerator pressure entrance, core and exit effect for 25,2 m^3/h are calculated, see Table 1.

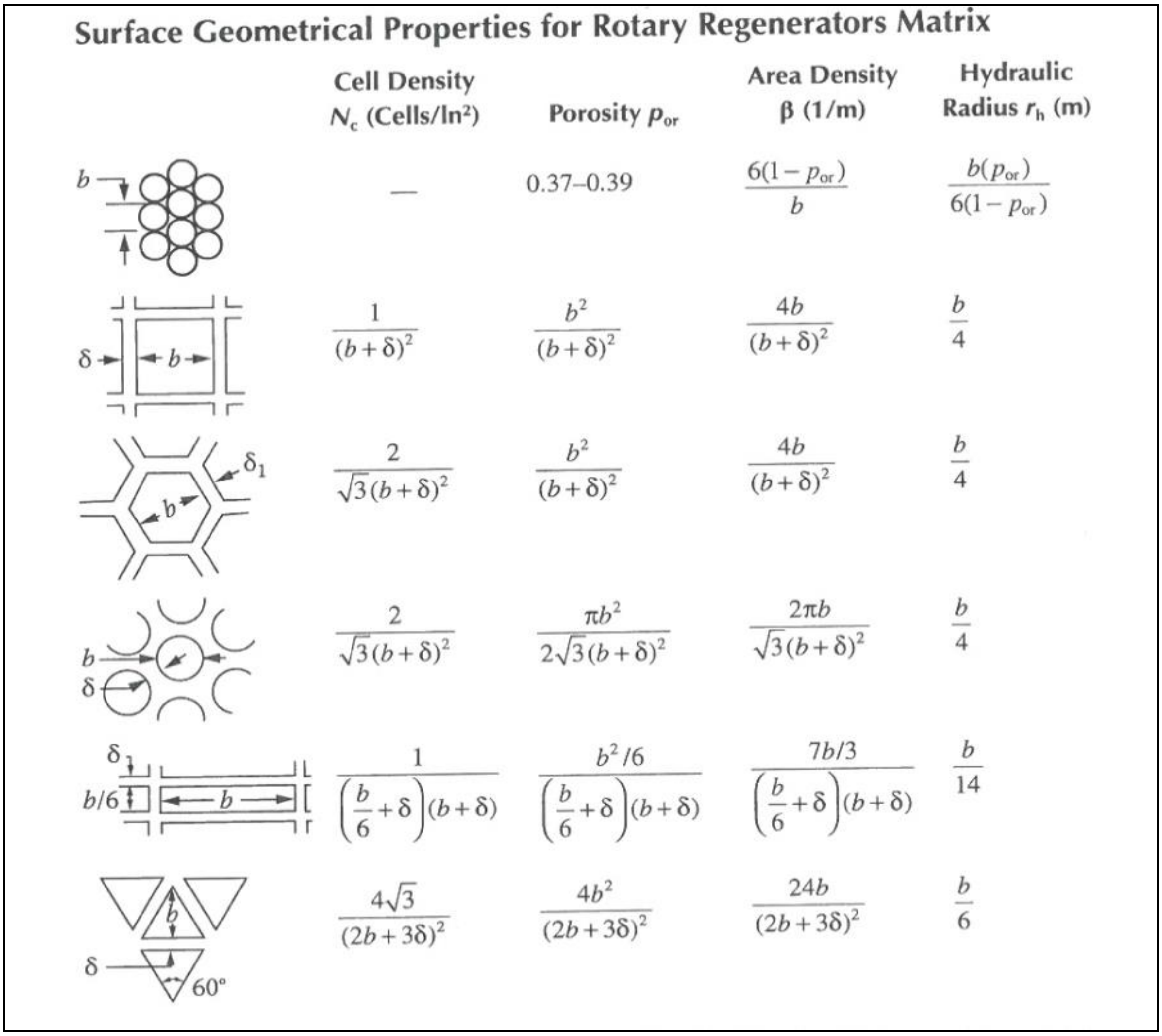
Entrance effect	Core friction	Exit effect
[%]	[%]	[%]
15	94	-9

Table 1. Pressure loss distribution in prototype regenerator.

It can be observed that the core friction is dominating term, entrance effect contributes to pressure loss and exit effect contradict pressure loss. Results are with good agreement with expectations.

Sensitivity analysis

In this chapter is presented sensitivity analysis of regenerator heat exchanger taking into account several parameters: exchanger geometry (total), matrix shape, material properties, air flow, shifting time, area density. Parameters investigated are efficiency to regenerate heat and pressure drop on the exchanger. In the sensitivity analysis it is assumed that only the one parameter varies at the time.
Typical surface geometries of the exchanger were investigated. The inspiration was taken from [2] and the potential candidates are presented in Fig. 3. From Fig. 3 following geometries were investigated: square, pentagon, tube (with wall) and rectangular (called flat plate in this study). For the comparison purpose, area density parameter was kept the same for all types of investigated regenerators (but porosity was not kept the same).



Surface Geometrical Properties for Rotary Regenerators Matrix

	Cell Density N_c (Cells/In²)	Porosity p_{or}	Area Density β (1/m)	Hydraulic Radius r_h (m)
	—	0.37–0.39	$\frac{6(1-p_{or})}{b}$	$\frac{b(p_{or})}{6(1-p_{or})}$
	$\frac{1}{(b+\delta)^2}$	$\frac{b^2}{(b+\delta)^2}$	$\frac{4b}{(b+\delta)^2}$	$\frac{b}{4}$
	$\frac{2}{\sqrt{3}(b+\delta)^2}$	$\frac{b^2}{(b+\delta)^2}$	$\frac{4b}{(b+\delta)^2}$	$\frac{b}{4}$
	$\frac{2}{\sqrt{3}(b+\delta)^2}$	$\frac{\pi b^2}{2\sqrt{3}(b+\delta)^2}$	$\frac{2\pi b}{\sqrt{3}(b+\delta)^2}$	$\frac{b}{4}$
	$\frac{1}{\left(\frac{b}{6}+\delta\right)(b+\delta)}$	$\frac{b^2/6}{\left(\frac{b}{6}+\delta\right)(b+\delta)}$	$\frac{7b/3}{\left(\frac{b}{6}+\delta\right)(b+\delta)}$	$\frac{b}{14}$
	$\frac{4\sqrt{3}}{(2b+3\delta)^2}$	$\frac{4b^2}{(2b+3\delta)^2}$	$\frac{24b}{(2b+3\delta)^2}$	$\frac{b}{6}$

Fig. 3 Surface geometries of typical heat exchanger geometries as proposed in [2]

In the sensitivity study presented in this report, 5 different typical materials used to manufacture heat exchangers were studied. Their thermal properties, density (rho), thermal conductivity (λ) and specific heat capacity (Cp) are collected and presented in Table 2.

HEAT EXCHANGER MATERIALS			
	rho	λ	Cp
	[kg/m³]	[W/(mK)]	[kJ/kgK]
HDP (Polyethylene)	930	0,5	1,9
Ceramics (low thermal conductivity)	2000	5	0,9
Ceramics (high thermal conductivity)	7850	50	0,9
Aluminum	2730	155	0,893
Copper	8960	400	0,385

Table 2. Thermal properties of materials investigated as potential candidates to manufacture regenerator.

Sensitivity 1.1

GEOMETRY:
Length: 6 /step 2/ 24 cm
Width: 24 cm
Height: 8 cm
Plate thickness: 1 mm
Area density: 577

AIR FLOW:
Volume flow: 25,2 [m³/h]

OTHER:
Shifting time (total shifting time): 70 [s]

MATERIAL:
HDP, Ceramic – low λ, Ceramic – high λ, Aluminum, Copper.

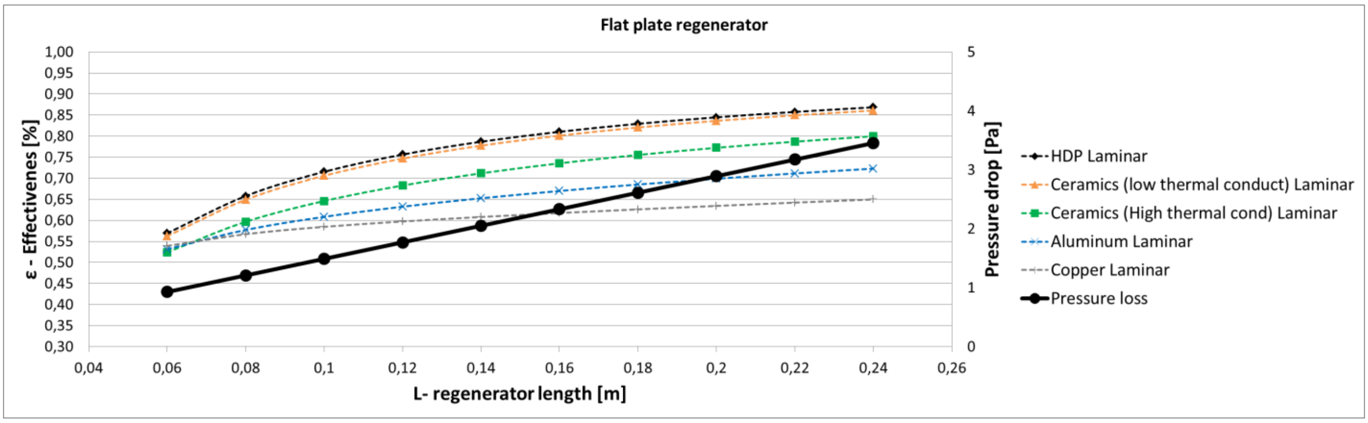


Fig 4. Sensitivity 1.1 – Flat plate regenerator.

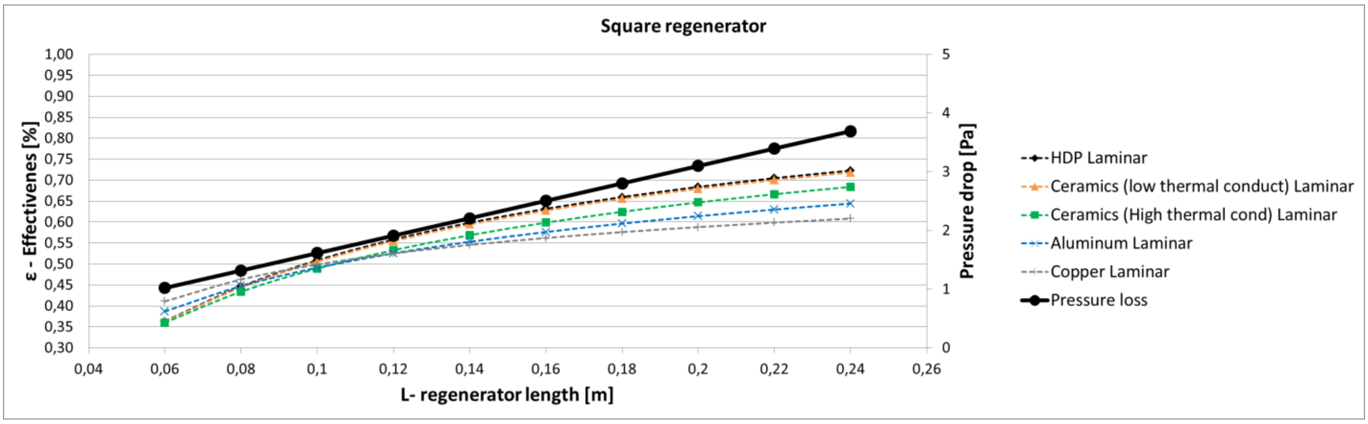


Fig 5. Sensitivity 1.1 – Square regenerator.

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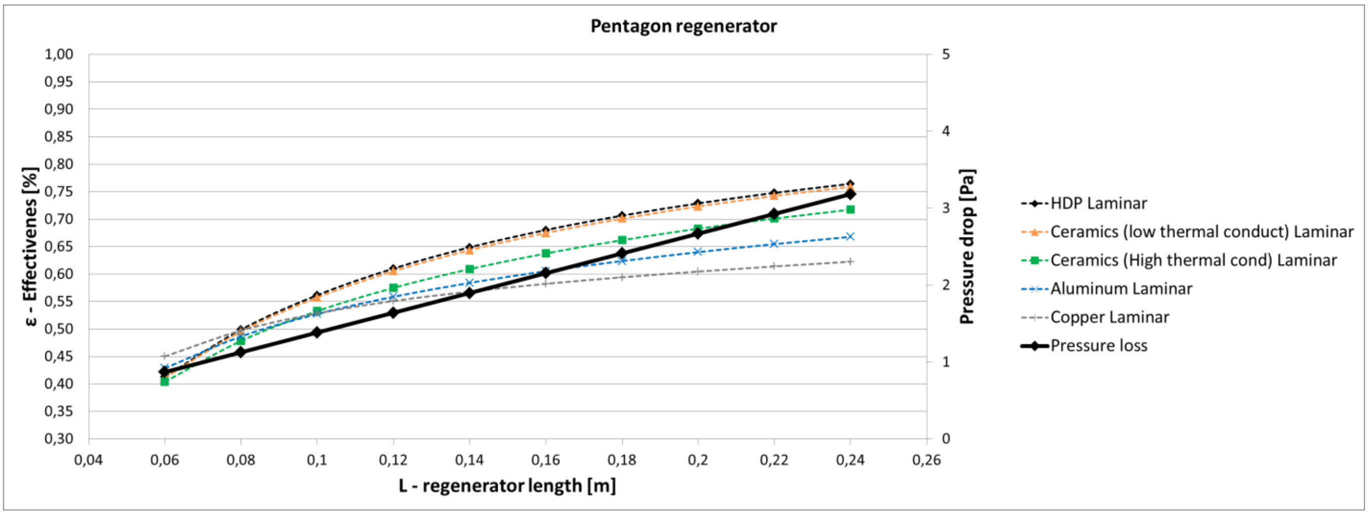

Fig 6. Sensitivity 1.1 – Pentagon regenerator.

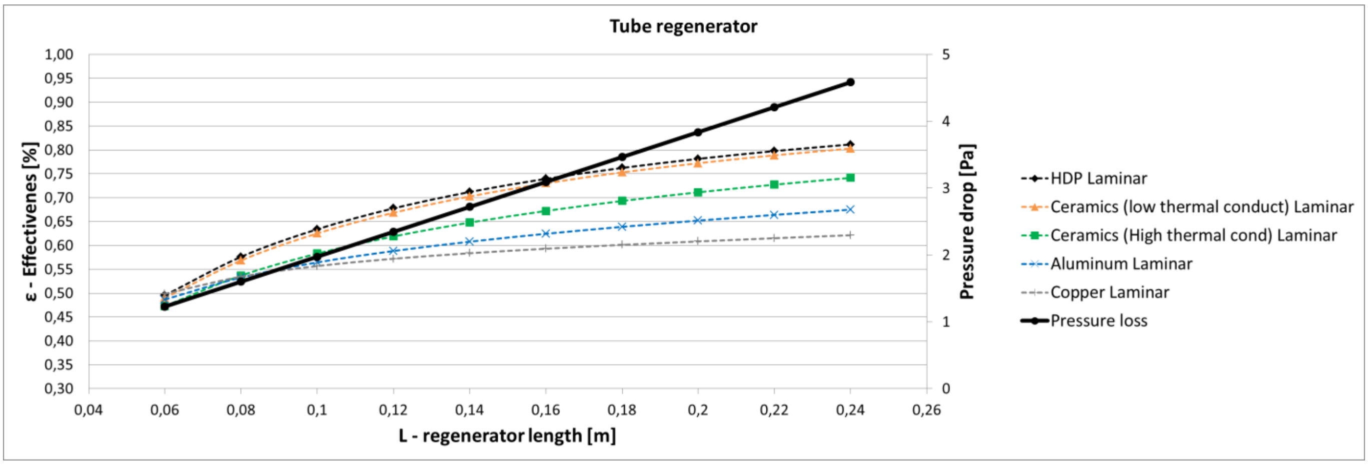

Fig 7. Sensitivity 1.1 – Tube regenerator.

Summary

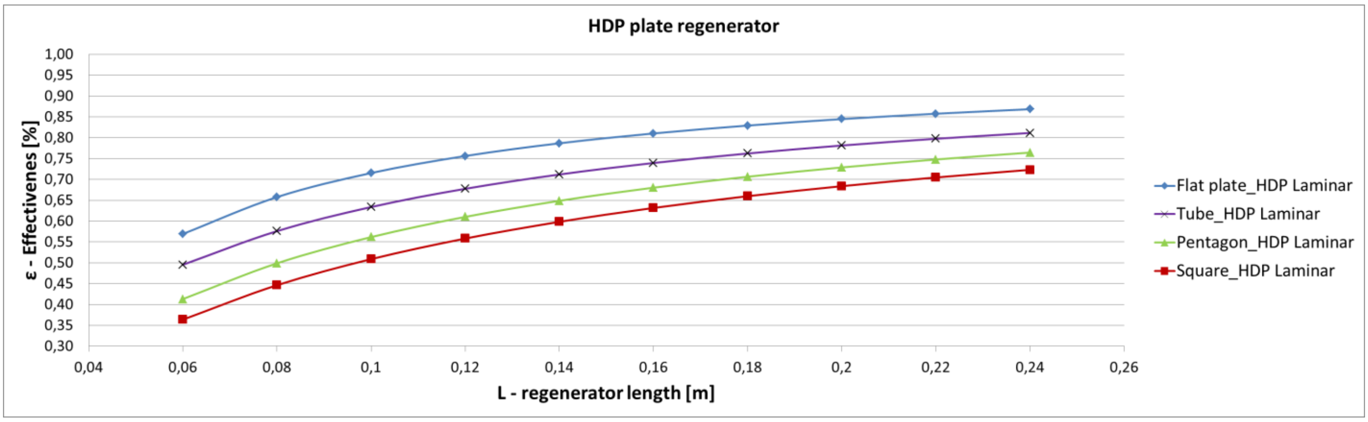

Fig 8. Sensitivity 1.1 – Efficiency summary.

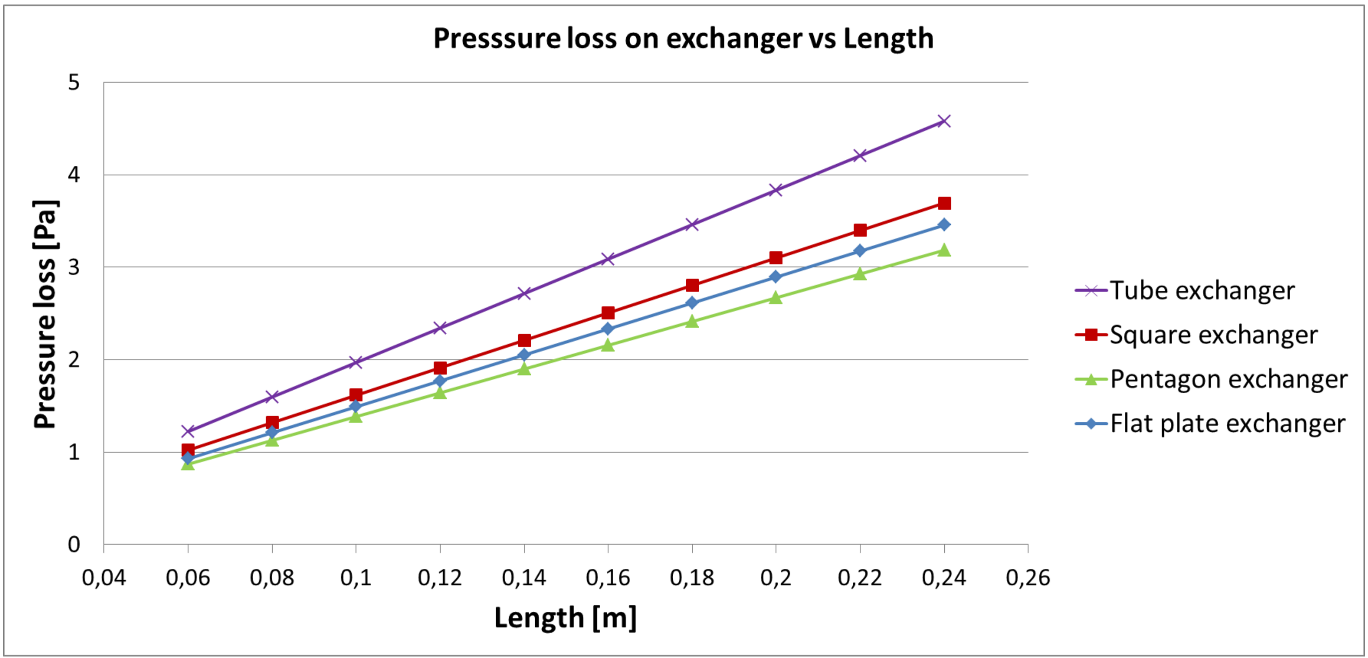

Fig 9. Sensitivity 1.1 – Pressure loss summary.

Sensitivity 1.2

GEOMETRY:
Length: 18 cm
Width: 24 cm
Height: 8 cm
Plate thickness: 1 mm
Area density 577 – 728

AIR FLOW:
Volume flow: 25,2 [m³/h]

OTHER:
Shifting time (total shifting time): 70 [s]

MATERIAL:
HDP, Ceramic – low λ, Ceramic – high λ, Aluminum, Copper.

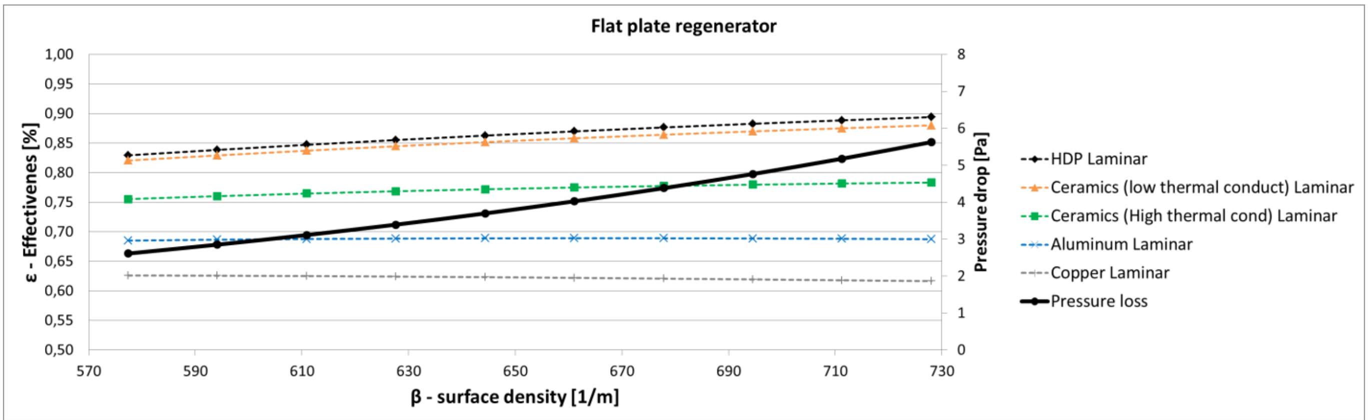

Fig 10. Sensitivity 1.2 – Flat plate regenerator.

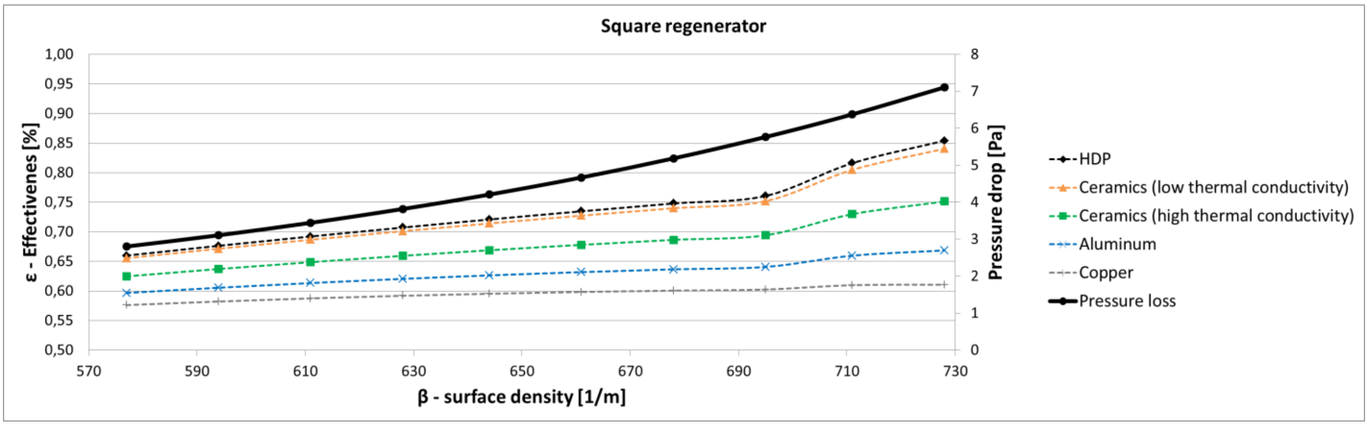

Fig 11. Sensitivity 1.2 – Square regenerator.

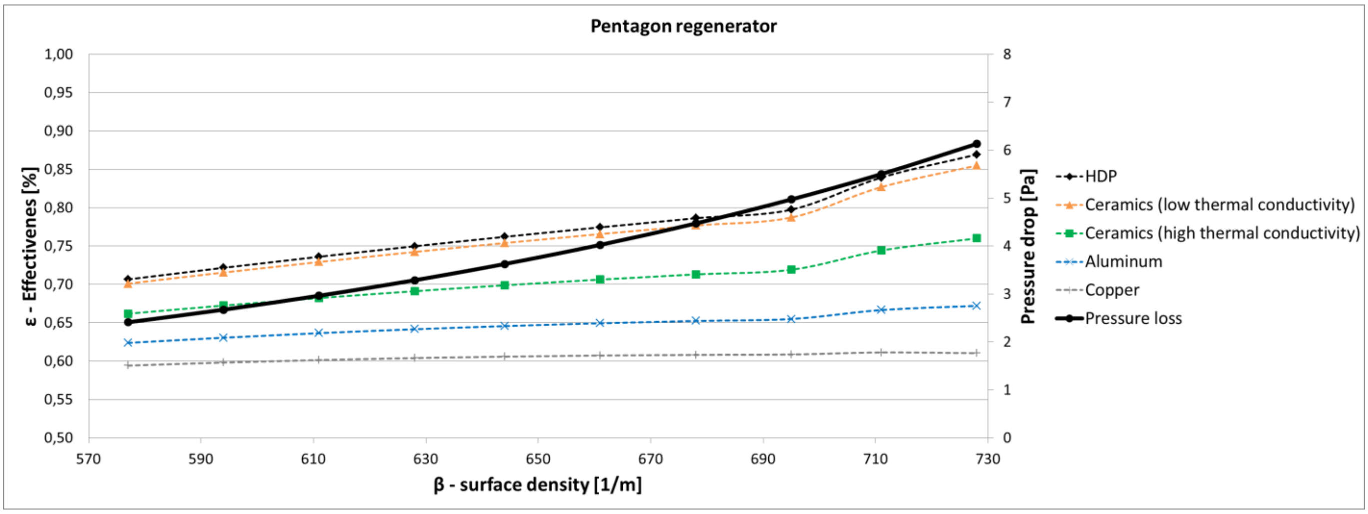

Fig 12. Sensitivity 1.2 – Pentagon regenerator.

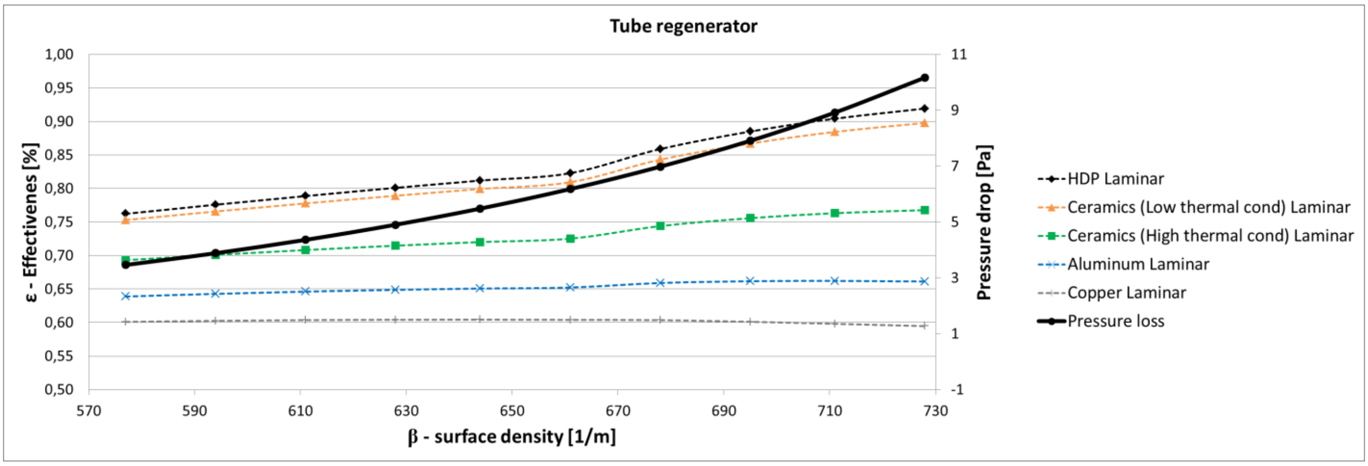

Fig 13. Sensitivity 1.2 – Tube regenerator.

Summary

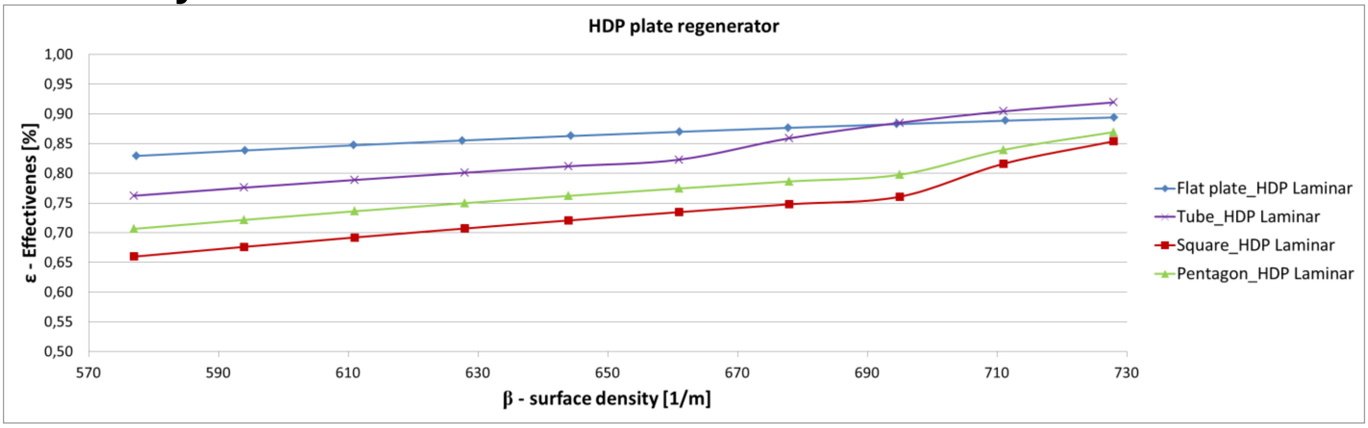

Fig 15. Sensitivity 1.1 – Efficiency summary.

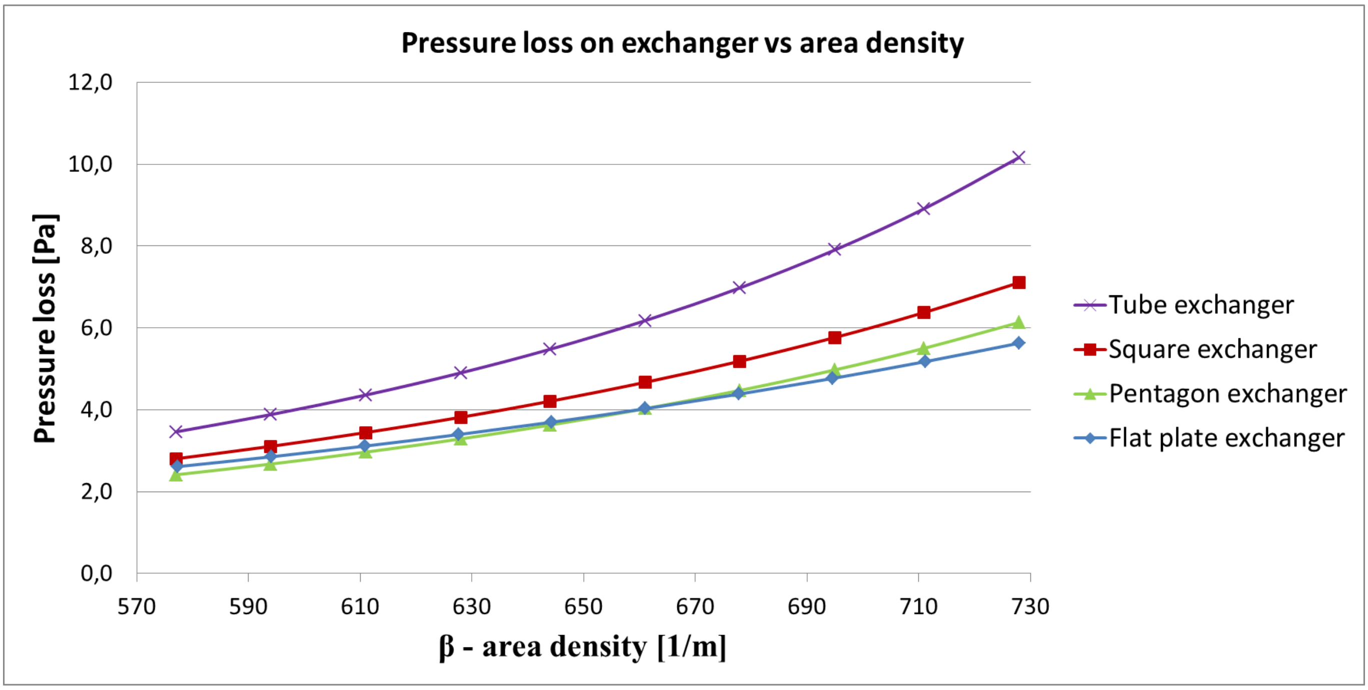

Fig 14. Sensitivity 1.2 – Pressure loss summary.

Sensitivity 1.3

GEOMETRY:
Length: 18 cm
Width: 24 cm
Height: 8 cm
Plate thickness: 1 mm
Area density 577

AIR FLOW:
Volume flow: 16/step 2/34 [m³/h]

OTHER:
Shifting time (total shifting time): 70 [s]

MATERIAL:

HDP, Ceramic – low λ, Ceramic – high λ, Aluminum, Copper.

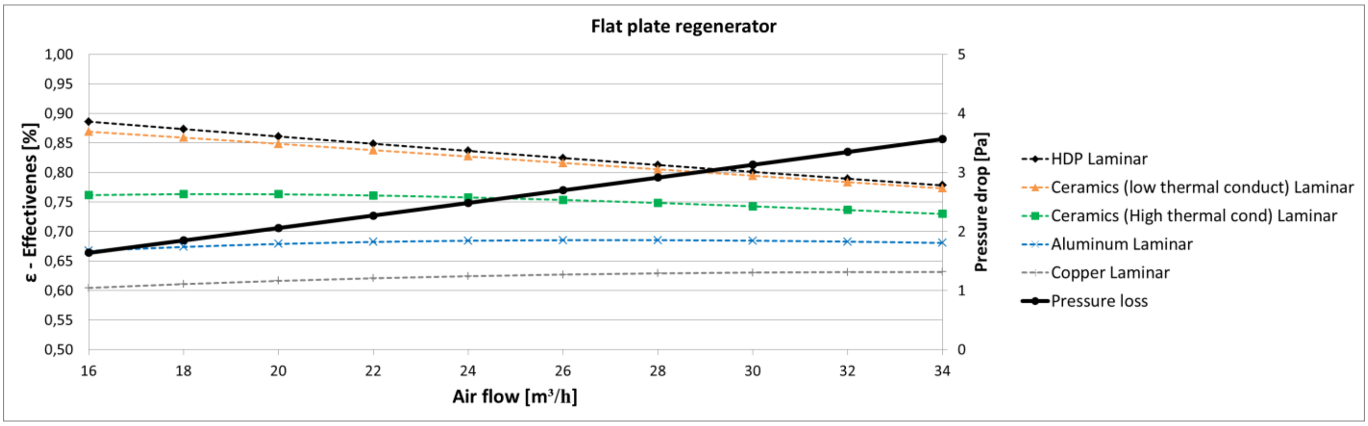

Fig 16. Sensitivity 1.3 – Flat plate regenerator.

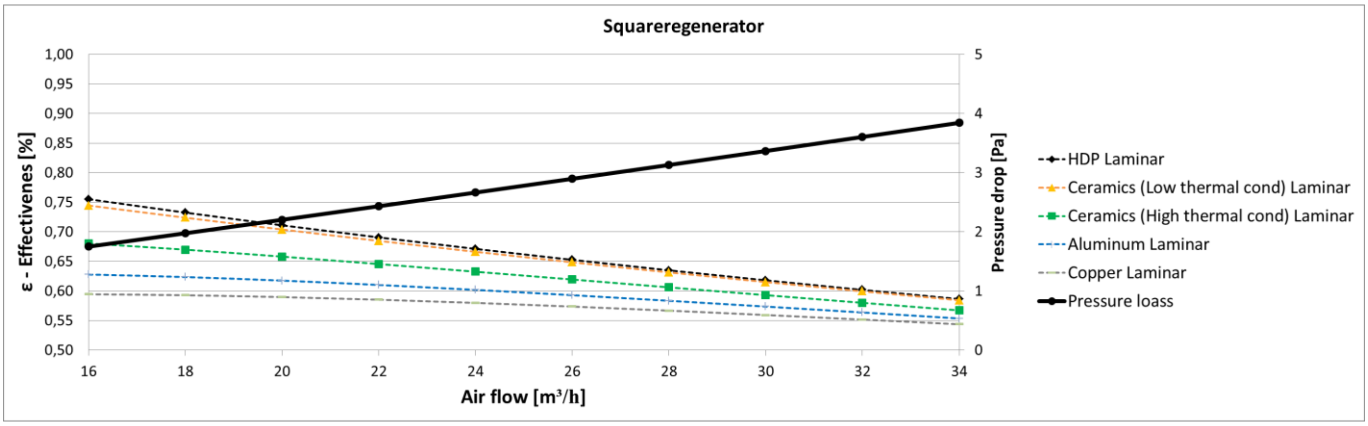

Fig 17. Sensitivity 1.3 – Square regenerator.

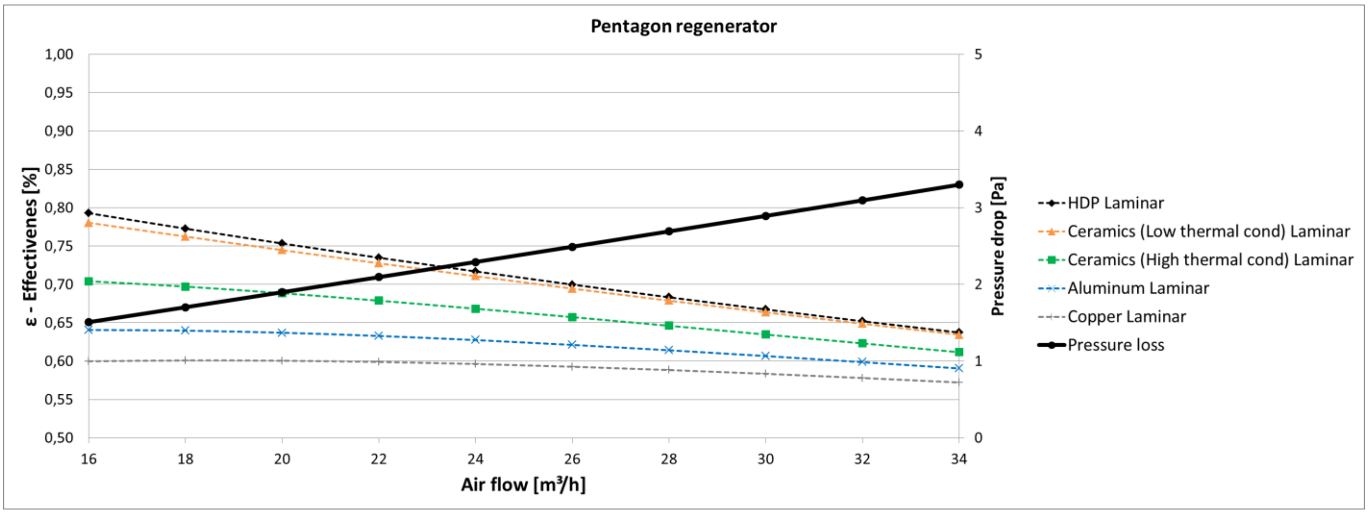

Fig 18. Sensitivity 1.3 – Pentagon regenerator.

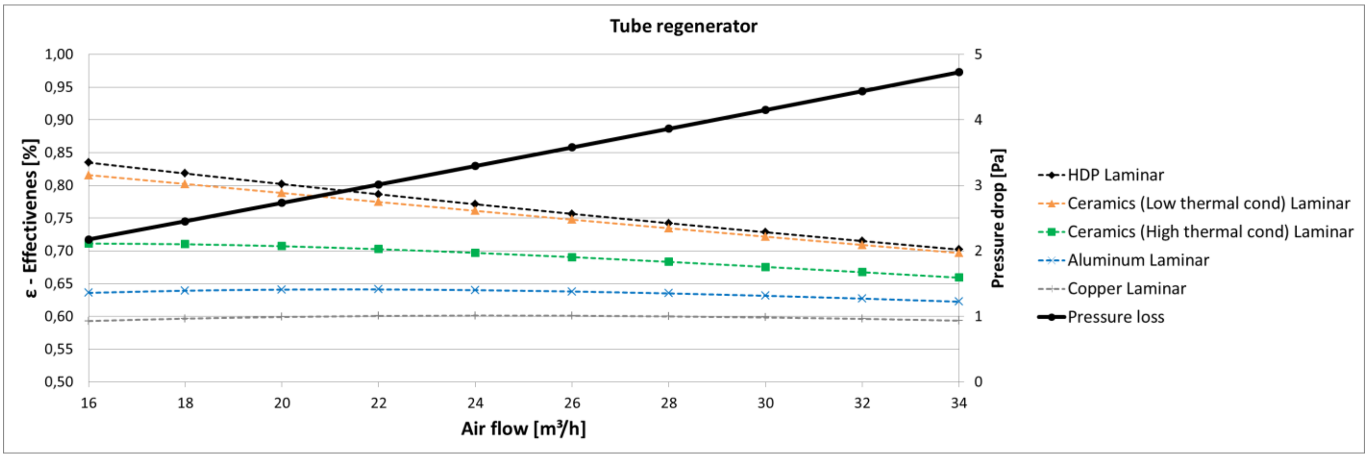

Fig 19. Sensitivity 1.3 – Tube regenerator.

Summary

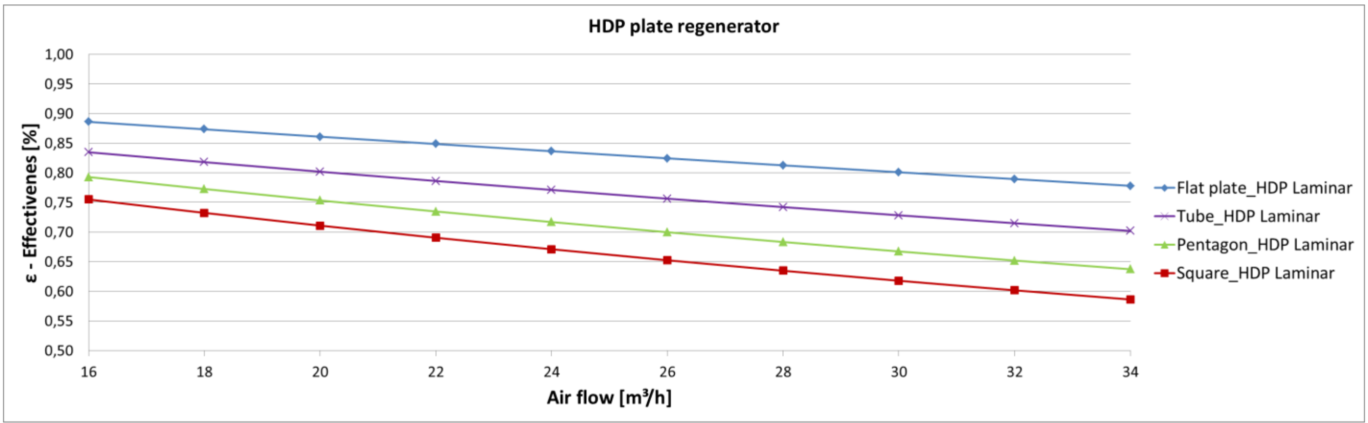

Fig 20. Sensitivity 1.3 – Efficiency summary.

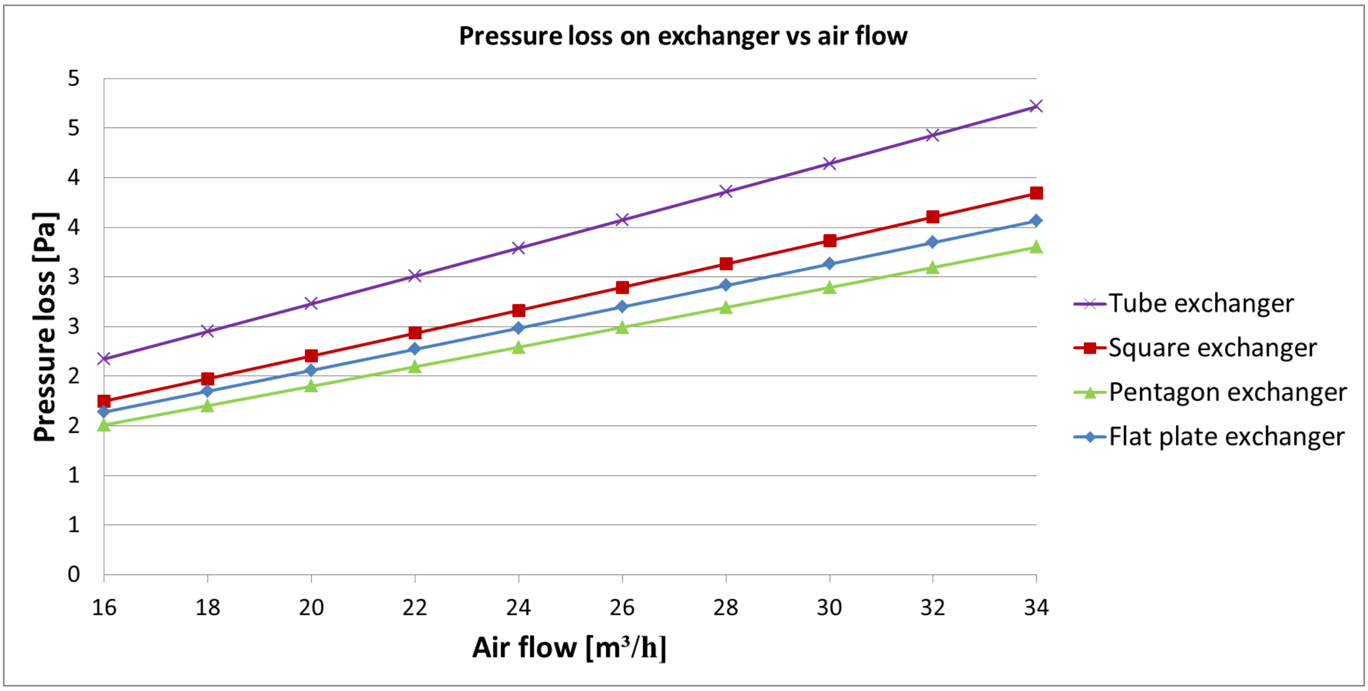

Fig 21. Sensitivity 1.3 – Pressure loss summary.

Sensitivity 1.4

GEOMETRY:
Length: 18 cm
Width: 24 cm
Height: 8 cm
Plate thickness: 1 mm
Area density 577

AIR FLOW:
Volume flow: 25,2 m^3/h

OTHER:
Shifting time (total shifting time): 60/step 20/ 240 [s]

MATERIAL:
HDP, Ceramic – low λ, Ceramic – high λ, Aluminum, Copper.

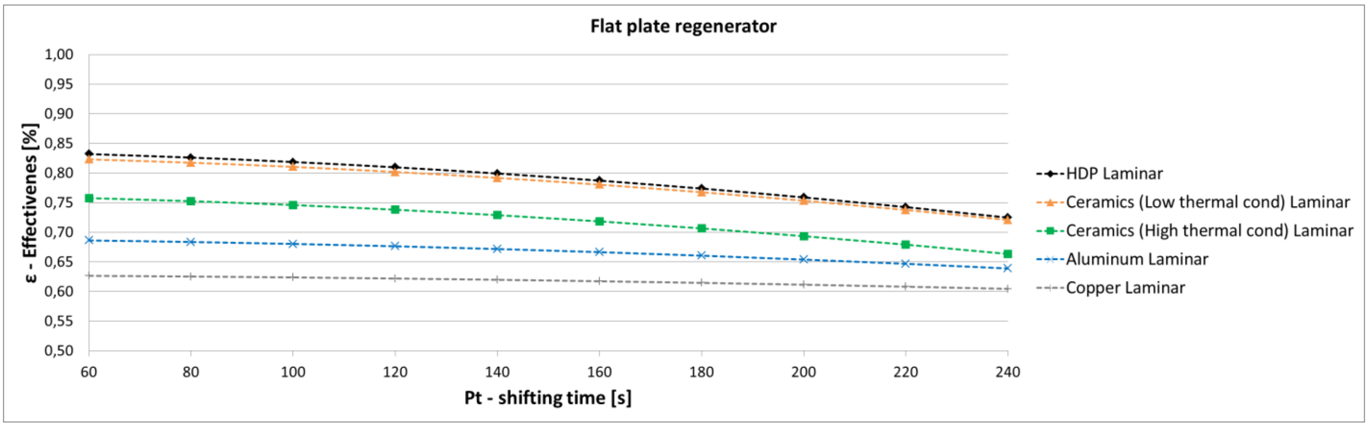

Fig 22. Sensitivity 1.4 – Flat plate regenerator.

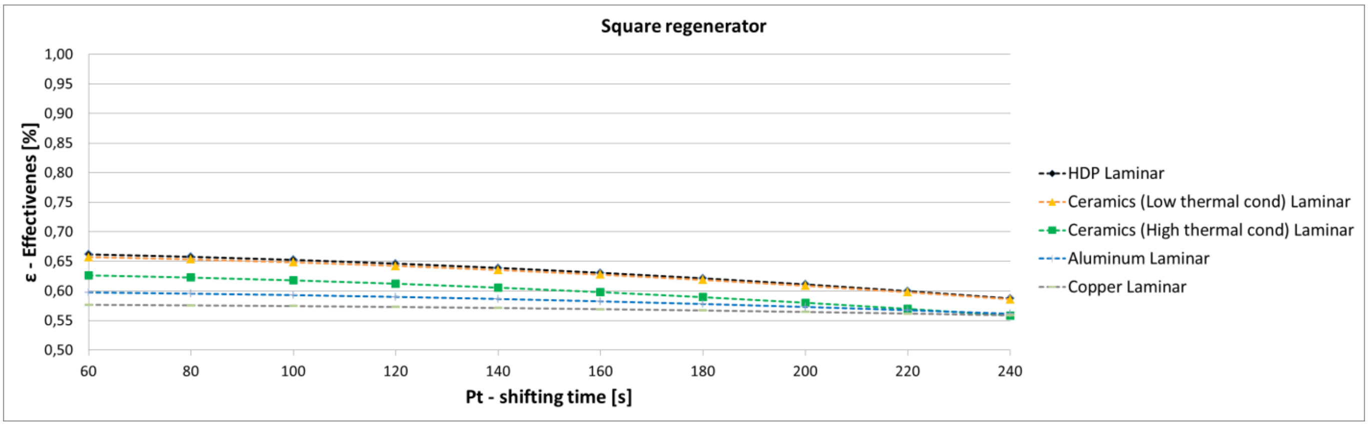

Fig 23. Sensitivity 1.4 – Square regenerator.

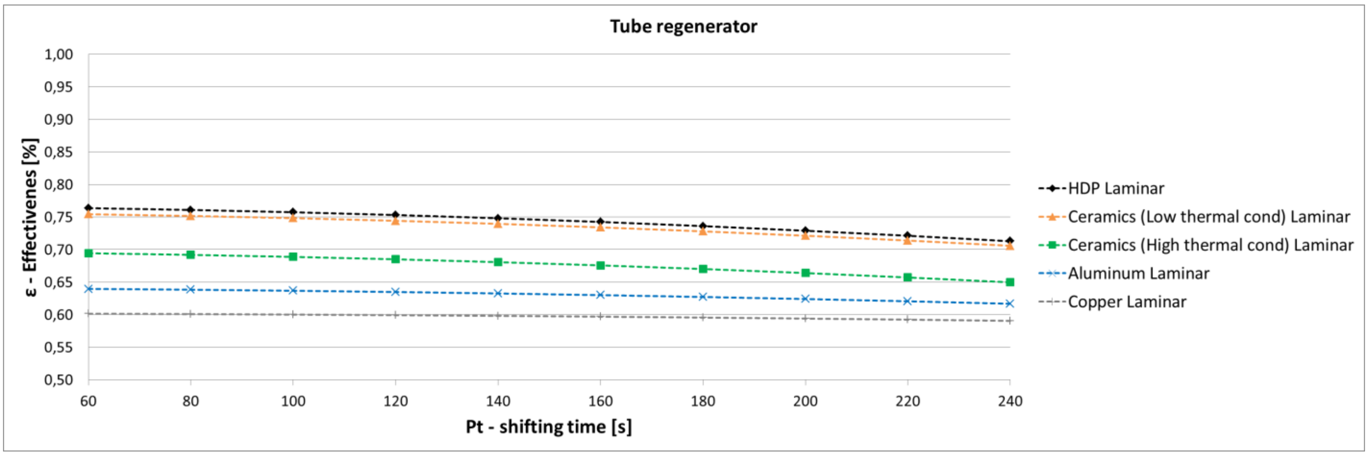

Fig 24. Sensitivity 1.4 – Tube regenerator.

Conclusions

Presented sensitivity study indicates that HDP and ceramics with low thermal conductivity are good material candidates to manufacture regenerator heat exchangers. The reason why efficiency is one of the highest for these materials is due to not so high thermal conductivity that decreases longitudinal heat loss. For ceramics with high thermal conductivity, aluminum or copper the high thermal conductivity contributes to high longitudinal heat losses and as a result to a lower heat regeneration efficiency.
What is more, based on presented analytical calculations, regenerator with flat plate geometry, obtains highest efficiency and at the same time lowest pressure drop.
The first round of sensitivity analysis indicates that to reach efficiency higher than 85% for considered air flow rate of 25,2 m^3/h, regenerator must have larger surface area than presented prototype model. The higher efficiency can be obtained in 2 manners. The first manner will increase pressure loss through regenerator and to this method accounts: increase of length in airflow direction, increase of number of plates with unchanged thickness. The second manner increases efficiency and keeps pressure drop unchanged or even lower, and this can be obtained by increasing regenerator height and/or width or increase of number of plates and at the same time decrease their thickness.
There is also third manner, that requires reduction of volume air flow through regenerator, but this one is not considered as indoor climate, would suffer due to that change.
Lastly, it can be observed that shifting time up to 100 s does not have significant influence on efficiency (it should be stated that this is valid for plate thickness of 1mm and can vary with plate thickness).

Second round of sensitivity analysis

The aim of the project is to develop regenerator unit that could ensure entire decentralized ventilation unit to deliver minimum heat regeneration efficiency of 85%. The decentralized ventilation unit is mounted in the roof just above roof window and therefore it is in direct contact with outdoor air. This will cause some heat losses that are estimated to reduce entire unit heat regeneration efficiency at approximately 5%. Therefore, regenerator heat efficiency is estimated to have to be around 90%.

The second round of sensitivity analysis is focused on investigation – how to reach very high thermal efficiency, up to 90%, and not increase pressure loss on regenerator heat exchanger?

In the second round sensitivity analysis is conducted for two air flows: 16 and 25,2 [m³/h].
In the second round sensitivity analysis is conducted only for HDP material and plate geometry.

Sensitivity 2.1

GEOMETRY:
Length: 18/ step 1/ 26 cm
Width: 24 cm
Height: 8 cm
Plate thickness: 1 mm
Number of plates: 70
Area density 577

AIR FLOW:
Volume flow: 16 and 25,2 [m^3/h]

OTHER:
Shifting time 70 s.

MATERIAL:
HDP

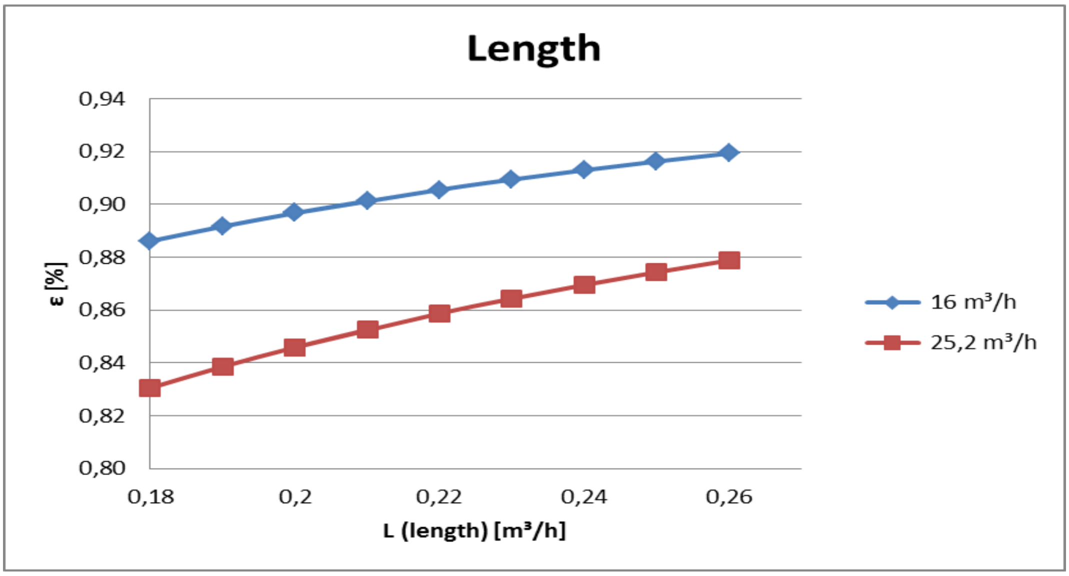

Fig. 25 . Regeneration heat efficiny vs. regenerator length

	16 m³/h		25,2 m³/h	
L depth	ε	Pressure drop	ε	Pressure drop
[m]	[-]	[Pa]	[-]	[Pa]
0,18	**0,89**	**1,64**	**0,83**	**2,59**
0,19	**0,89**	**1,73**	**0,84**	**2,73**
0,2	**0,90**	**1,82**	**0,85**	**2,87**
0,21	**0,90**	**1,91**	**0,85**	**3,01**
0,2	**0,90**	**1,82**	**0,85**	**2,87**
0,22	**0,91**	**1,99**	**0,86**	**3,15**
0,23	**0,91**	**2,08**	**0,86**	**3,29**
0,24	**0,91**	**2,17**	**0,87**	**3,43**
0,25	**0,92**	**2,26**	**0,87**	**3,57**
0,26	**0,92**	**2,35**	**0,88**	**3,70**

Table 3 . Regeneration heat efficiny and pressure loss vs. regenerator length

Sensitivity 2.2

GEOMETRY:
Length: 18
Width: 24 cm
Height: 8 – 10 cm
Plate thickness: 1 mm
Number of plates: 70
Area density 577

AIR FLOW:
Volume flow: 16 and 25,2 [m^3/h]

OTHER:
Shifting time 70 s.

MATERIAL:HDP

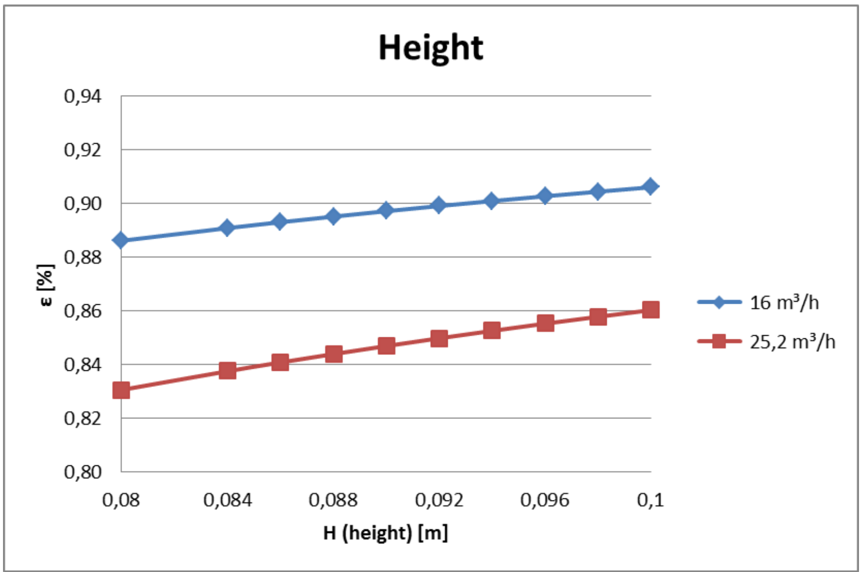

Fig. 26. Regeneration heat efficiny vs. regenerator height.

	16 m³/h		25,2 m³/h	
H (height)	ε	Pressure drop	ε	Pressure drop
[m]	[-]	[Pa]	[-]	[Pa]
0,08	0,89	1,64	0,83	2,59
0,084	0,89	1,55	0,84	2,46
0,086	0,89	1,51	0,84	2,39
0,088	0,90	1,48	0,84	2,33
0,09	0,90	1,44	0,85	2,28
0,092	0,90	1,41	0,85	2,22
0,094	0,90	1,38	0,85	2,17
0,096	0,90	1,34	0,86	2,12
0,098	0,90	1,32	0,86	2,07
0,1	0,91	1,29	0,86	2,03

Table 4. Regeneration heat efficiny and pressure loss vs. regenerator height.

Sensitivity 2.3

GEOMETRY:
Length: 18
Width: 24 cm
Height: 8 cm
Plate thickness: 1 mm
Number of plates: 70/step 2/88
Area density 577 - 728

AIR FLOW:
Volume flow: 16 and 25,2 [m^3/h]

OTHER:
Shifting time 70 s.

MATERIAL:HDP

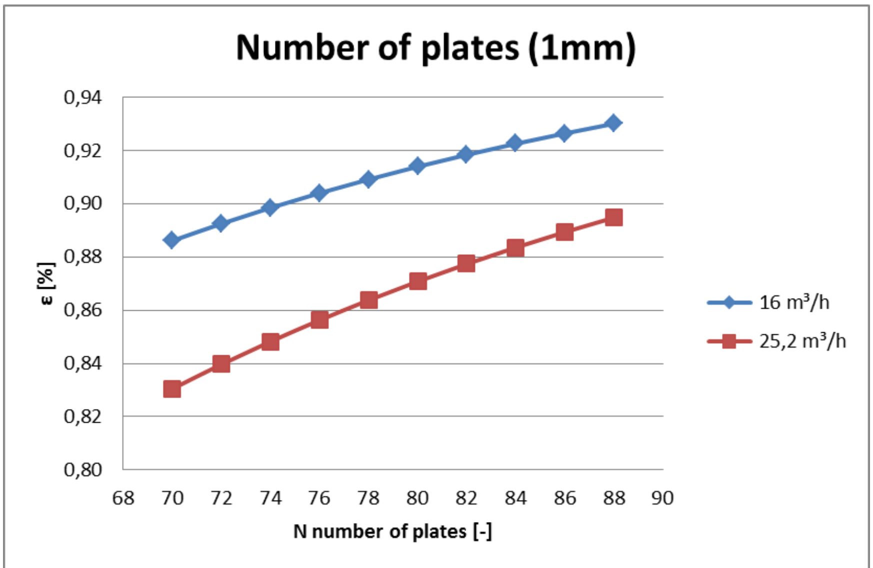

Fig. 27 . Regeneration heat efficiny vs. number of 1 mm thick plates.

		16 m³/h			25,2 m³/h	
N number of plates		ε	Pressure drop		ε	Pressure drop
[m]		[-]	[Pa]		[-]	[Pa]
70		**0,89**	**1,64**		**0,83**	**2,59**
72		**0,89**	**1,79**		**0,84**	**2,83**
74		**0,90**	**1,96**		**0,85**	**3,09**
76		**0,90**	**2,13**		**0,86**	**3,37**
78		**0,91**	**2,33**		**0,86**	**3,67**
80		**0,91**	**2,53**		**0,87**	**3,99**
82		**0,92**	**2,76**		**0,88**	**4,35**
84		**0,92**	**3,00**		**0,88**	**4,73**
86		**0,93**	**3,26**		**0,89**	**5,14**
88		**0,93**	**3,55**		**0,89**	**5,58**

Table 5. Regeneration heat efficiny and pressure loss vs. number of 1mm thick pates.

Sensitivity 2.4

GEOMETRY:
Length: 18
Width: 24 cm
Height: 8 cm
Plate thickness: 0,5 mm
Number of plates: 70/step 5/115
Area density 577 - 954

AIR FLOW:
Volume flow: 16 and 25,2 [m^3/h]

OTHER:
Shifting time 70 s.

MATERIAL:HDP

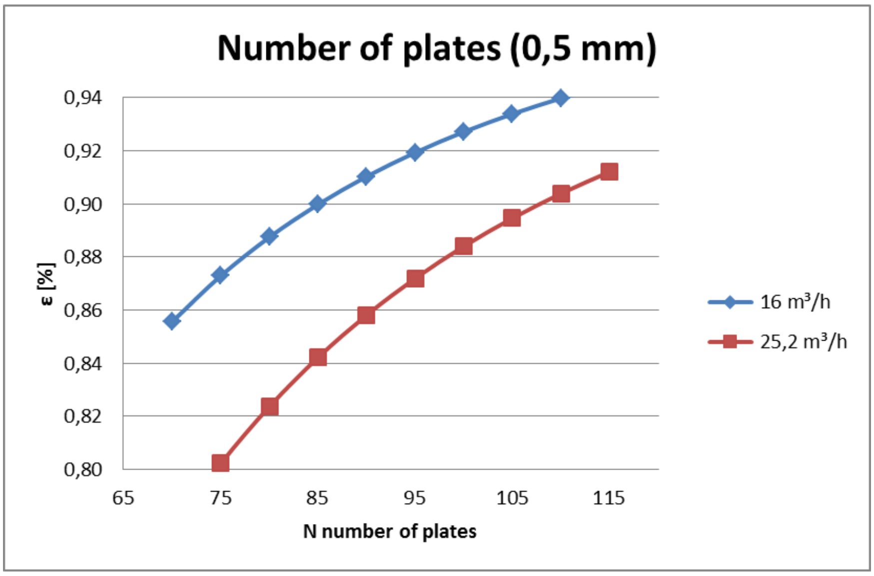

Fig. 28. Regeneration heat efficiny vs. number of 0,5 mm thick plates.

N number of plates		16 m³/h			25,2 m³/h	
		ε	**Pressure drop**		**ε**	**Pressure drop**
[m]		**[-]**	**[Pa]**		**[-]**	**[Pa]**
70		**0,86**	**0,95**		**0,78**	**1,50**
75		**0,87**	**1,12**		**0,80**	**1,77**
80		**0,89**	**1,31**		**0,82**	**2,07**
85		**0,90**	**1,53**		**0,84**	**2,42**
90		**0,91**	**1,78**		**0,86**	**2,80**
95		**0,92**	**2,05**		**0,87**	**3,22**
100		**0,93**	**2,35**		**0,88**	**3,70**
105		**0,93**	**2,69**		**0,89**	**4,23**
110		**0,94**	**3,07**		**0,90**	**4,81**
115		**0,94**	**3,48**		**0,91**	**5,47**

Table 6. Regeneration heat efficiny and pressure loss vs. number of 0,5 mm thick plates.

Sensitivity 2.5

GEOMETRY:
Length: 18
Width: 24 cm
Height: 8 cm
Plate thickness: 0,5 mm
Number of plates: 70/step 5/115
Area density 577 - 954

AIR FLOW:
Volume flow: 16 and 25,2 [m^3/h]

OTHER:
Shifting time 70 and 140 s.

MATERIAL:HDP

		1mm thick plate			**0,5 mm thick plate**		
		70 s	**140 s**		**70 s**	**140 s**	
N number of plates		ε	ε	**Δε**	**ε**	ε	**Δε**
[m]		[%]	**[%]**	**[%]**	**[%]**	**[%]**	**[%]**
70		**0,83**	**0,80**	**-0,03**	**0,78**	**0,67**	**-0,11**
75		**0,85**	**0,83**	**-0,03**	**0,80**	**0,70**	**-0,10**
80		**0,87**	**0,85**	**-0,02**	**0,82**	**0,74**	**-0,09**
85		**0,89**	**0,86**	**-0,02**	**0,84**	**0,76**	**-0,08**
90		**0,90**	**0,88**	**-0,02**	**0,86**	**0,78**	**-0,07**
95		**0,91**	**0,89**	**-0,02**	**0,87**	**0,80**	**-0,07**
100		**0,92**	**0,90**	**-0,02**	**0,88**	**0,82**	**-0,06**
105		**0,93**	**0,91**	**-0,02**	**0,89**	**0,84**	**-0,06**
110		**0,94**	**0,92**	**-0,01**	**0,90**	**0,85**	**-0,05**
115		**0,94**	**0,93**	**-0,01**	**0,91**	**0,86**	**-0,05**

Table 7. Regeneration heat efficiny and plate thickness of 1 mm and 0,5 mm.

Configurations reaching 90% heat recovery efficiency

Chosen regenerator configurations that result in 90% heat efficiency are presented in Table X.

Volume flow: 25,2 [m^3/h]
Shifting time 70 s.
Material: HDP

L depth	W width	H height	N number of plates	**ε**	**Pressure drop**
[m]	[m]	[m]	[m]	**[-]**	**[Pa]**
0,18	0,24	0,14	70	**0,90**	**1,43**
0,18	0,24	0,13	75	**0,90**	**1,93**
0,18	0,24	0,12	78	**0,90**	**2,39**
0,18	0,24	0,11	80	**0,90**	**2,86**
0,18	0,24	0,1	82	**0,90**	**3,45**
0,18	0,24	0,09	85	**0,90**	**4,38**
0,18	0,24	0,08	90	**0,90**	**6,11**

Table 8. Selected configurations reaching 90% heat recovery efficiency.

Conclusions

- It can be observed that increase of height and/or width of the regenerator is a win-win scenario. Efficiency increases and pressure drop decreases.
- It can be observed from the graphs in this report that at least two dimensions would have to be increased to reach efficiency of around 90% for air flow at 25,2 m^3/h. If only one dimension is manipulated then this dimension would probably become too large and regenerator would not fit to ventilation unit.
- To reach high efficiency and keep geometry unchanged or increased insignificantly number of plates would have to be increased.
- Increase of number of plates increases efficiency but at the same time increases also pressure loss. This can be counteracted by making plates thinner, however, if plates become thinner then regenerator becomes more sensitive to switching time. The longer switching time the lower efficiency becomes!

References

[1] R.K. Shah “Fundamentals of Heat Exchanger design”
[2] K. Thulukkanam book “ Heat Exchanger Design Handbook”