HEAT TRANSFER THROUGH EXCHANGER IN ERICSSON-BRAYTON PISTON ENGINE

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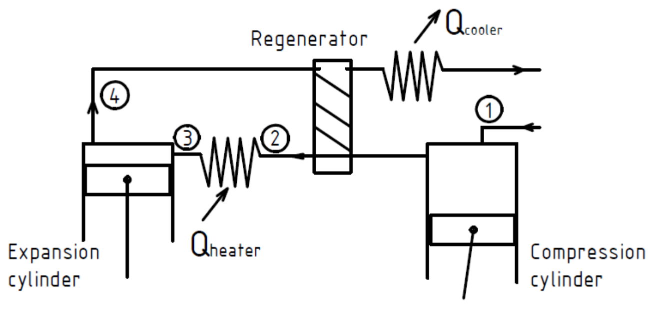
Abstract. Combined power generation or cogeneration is highly effective technology that produces heat and electricity in one device more efficient than separate production.Overall efectivity is growing by use of combined technologies of energy extraction - taking heat from flue gases and coolants of machines. Another problem is the dependence of such devices on fossil fuels as fuel for combustion turbines are the most common natural gas, kerosene and fuel for heating plants is coal. It is therefore necessary to seek for compensation today, which confirms the assumption in the future . At first glance, the obvious efforts to restrict the use of largely oil and change the type of energy used in transport . Another significant change is the increase in renewable energy - energy that is produced from renewable sources . Between machines gaining energy by unconventional way are belonging mainly steam engine , Stirling engine and Ericsson engine. In these machines , the energy is obtained by external combustion and engine performs work in a medium that receives and transmits energy from combustion or flue gases undirectly . The article deals with the principle of hot-air engines, their use in combined heat and electricity production from biomass and with heat exchangers as primary energy transforming element.

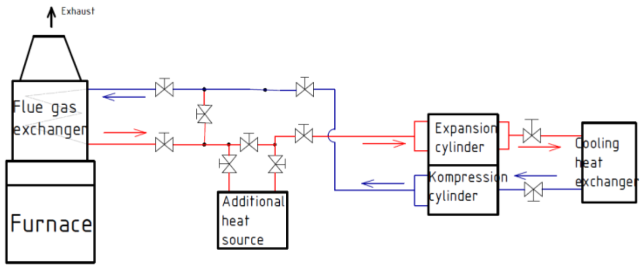
1 Micro-cogeneration unit with nonconventional engine

As power unit of micro-cogeneration devices are most used gas combustion engines, as fuel is used natural gas. Losses in electricity generation are mainly associated with imperfect energy transformation in burning fuel in an imperfect transformation of energy working medium in the turbine, also there are represented mechanical losses and loss of energy in transmission lines. The smallest losses have cogeneration plants. Cogeneration unit is a technical device, which is manufactured electric and thermal energy simultaneously. As an example may be mentioned cogeneration unit with an internal combustion gas engine. The engine burns the gas, thereby is gaining the mechanical power on the shaft to drive an electric generator. The engine has not a classic cooler, but the heat exchanger from which we obtain thermal energy. These heat exchangers are then connected in series circuit, where the working medium, usually water, is heated in several stages. Multistage heat recovery increases the overall efficiency of CHP unit and reduces the total cost of fuel. [1] As a possible alternative to the internal combustion engines are unconventional engines. They work with external combustion, or burning fuel does not take place in the working cylinder. This allows, unlike conventional internal combustion engines, control the course of combustion, and therefore its quality, which is reflected in the composition of air pollutants emitted to the atmosphere. The most known hot air engines are Stirling and Ericsson engine. Ericsson engine has posible modification, the Ericsson-Brayton engine. Ericsson engine is also external combustion engine. In contrast to Stirling engine it has two possible alternatives - open and closed. [2]. In the case of Stirling engine is immediately apparent dual function of regenerator. Regenerator works as heater and cooler while in Ericsson engine cooler and heater are separated. On Picture n.1 we can see Ericsson-Brayton engine with open cycle.



PICTURE N. 1. Scheme of Ericsson-Brayton hot air engine with open cycle.

The air is compressed in the compressor, flows through the heat exchanger, and where at constant pressure is receiving heat. Consequently, it is led to the expansion cylinder, which expands adiabatically and is acting work. Part of this work will be used to drive the compressor and part is used as mechanical work to drive an electric generator. As the heat source can be used almost any fuel, as it is the external combustion engine. Fuel is burned in a separate combustion chamber and heat energy is transformed through a heat exchanger to the working media. The working medium in open cycle, mostly dry air, is after passing the cycle discharged into the atmosphere. In a closed cycle the media after each cycle cools in refrigerant heat exchanger, where it gives heat energy and is fed back into the cycle [3]. With use of closed cycle we can improve the efficiency of heating equipment.



PICTURE N. 2. Scheme of Ericsson-Brayton hot air engine with open cycle.

Our proposed microcogeneration unit uses two heat exchangers, one is cooler and another is heater. The scheme can we see in Picture n. 2. Different purpose sets other requirements on the heat exchangers. The first requirement is to ensure optimal heat transfer between flowing media. The heat transfer is characterized by a heat transfer coefficient. This summary represents the characteristics of the heat exchanger, its layout and the flowing media. Coefficient depends on the characteristics of the media flowing, from the heat capacity, the selected konstruction option and in some cases is significantly influenced by the material used and the heat exchanger. The requirement is that the coefficient is the highest, while respecting the chosen solutions. Further requirements are then asked to compact size exchanger, the total pressure loss and also maintenance options are required.

2 Heat exchanger design

As first step we have set the working conditions of the CHP. Our apllication with Ericsson-Brayton hot air engine sets wide range of specifications, not only on the heat exchanger, but also on the whole system. The whole unit should supply energy for household. In the determining of the operating conditions we have preliminary set the highest temperatures from 500°C up to 620°C, according to [3], [5]. In this articles, autors presented highest temperature 600°C. Another autors [1] have presented systems with different working fluids and also different hot air engine configurations.Our system should work with closed cycle, with dry air as working fluid [4]. The closed cycle enables heat recovery from working fluid, so the regenerated heating power is bigger than in opened cycle, where the most part of heat energy is used to pre-heat the air after compression. We are assuming the temperature of the working fluid after expansion in range from 240°C to 320°C [4], [5]. For each working fluid, the dry air in the tubes and the exhaust gases outside the tubes, we have set the characteristically temperatures and physical properties. For the formula we use literature [6] and [7].

There are many ways how to compute the properties of flowing mediums. To determine the heat transfer we need to know the thermodynamic properties of flowing gas. It is important to determine the dynamic and kinematic viscosity. For heat transfer is also needed to know the thermal conductivity of the gas. There are several options of calculation, we used the relations according to [6], [7].

Dynamic viscosity :

$$\eta_{TP} = 1{,}0607 \cdot 10^{-6} \cdot T^{0{,}5} \cdot k_T \cdot k_p \qquad (1)$$

Kinematic viscosity:

$$\nu_{TP} = 304{,}52344 \cdot 10^{-6} \frac{T^{1{,}5}}{p} k_T k_P \qquad (2)$$

And the thermal conductivity:

$$\lambda = 1513{,}8151 \cdot 10^{-6} T^{0{,}5} (k_T k_P)^{1{,}5} \qquad (3)$$

The coeficients k_T and k_p are set for temperatures from 0°C up to 1000°C. The main difference to real values of parameters is up to 3%, so it is possible to say that the computation is accurate. In Table n. 1 we can see some values of coeficient k_T .

Tab. 1: Values of K_T for dry air by pressure 10^5 Pa

T [K]	t [°C]	K_T
373,15	100	1,054403
393,15	120	1,066696
413,15	140	1,075804
433,15	160	1,087817
453,15	180	1,103398

The values of the coeficient K_P are set for dry air by constant temperature. In Table n. 2 we can see some values of coeficient K_P .

Tab. 2: Values of K_p for dry air by temperature 273 K.

p [Pa]	p [bar]	K_p
10	10^{-4}	0,464348
10^2	10^{-3}	0,880435
10^3	10^{-2}	0,984783
10^4	10^{-1}	0,993333
10^5	1	1,000000
$5 . 10^5$	5	1,003509

For the computation of heat transfer we need also know the density of flowing air, or flue gases. There are also many methods. We have used two of them. As first is possible to read the right values in tables, that are computed, or measured. In Table n.3 are some values of air properties. The second column is density. The values that are not in table we can compute as aproximation.

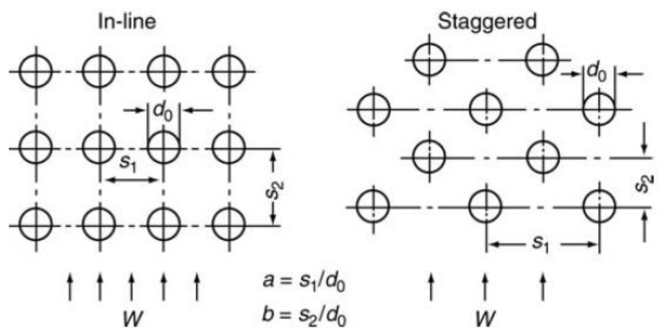
Tab. 3 Physical properties for dry air by pressure 100 kPa

t [°C]	ρ [kg/m³]	c [J/kg.K]	λ . 10² [W/(m.K)]	a . 10⁶ [m²/s]
0	1,275	1005	2,37	18,5
10	1,23	1005	2,45	19,82
20	1,188	1010	2,52	21
40	1,112	1013	2,65	23,53
60	1,046	1017	2,8	26,32
80	0,986	1020	2,93	29,13
100	0,934	1022	3,07	32,16
120	0,886	1024	3,2	35,27
140	0,843	1027	3,33	38,46
160	0,804	1030	3,44	41,54
180	0,769	1034	3,57	44,9
200	0,736	1037	3,7	48,48

We can compute density also from known parameters. In next formulas is density expressed as function of dynamic and kinematic viscosity:

$$\rho = \frac{\mu}{\upsilon} \qquad (4)$$

So in this way we can define properties of flowing mediums. Very important is also define the geometrical properties or features of the choosen type of exchanger. There are many basic concepts of exchangers. We can divide them into many classes based on the geometrical features, the heat transfer method etc. For our purpose we have selected pipe exchanger. Difference is, if the tubes are straight or staggered, or partly staggered. It is characterized with dimensionless constants a and b.



PICTURE N. 3. Lateral and longitudinal spacing in tube bundles.

If the tube bundle has horizontal spacing "s_1" and vertical spacing "s_2", we can characterize the bundle with these constants:

$$a = \frac{s_1}{d_0} \qquad (5)$$

$$b = \frac{s_2}{d_0} \qquad (6)$$

$$\psi = 1 - \frac{\pi}{4.a} \qquad (7)$$

Also we can define the streamed length "l", that can be expressed as length of flow path transversed over a single tube [7] :

$$l = \frac{\pi}{2}.d_o \qquad (8)$$

Another difference can we see in the non-dimensional criteria. Reynolds number is characterizing the flowing medium and the type of flow. It depends on flow velocity and also on the geometry. For heat transfer through tubes in bundle we can use following Reynolds number criteria:

$$Re = \frac{w.l}{\psi.\nu} \qquad (9)$$

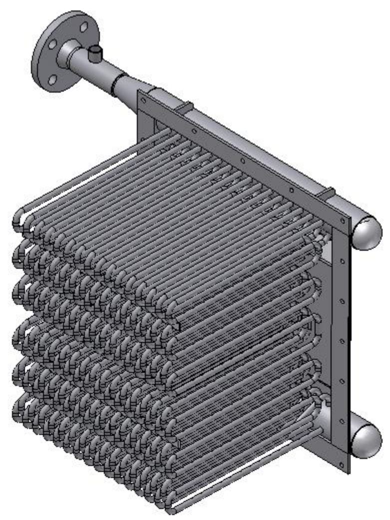
Nusselt number is characterizing the heat transfer. If the turbulence in the inflowing medium is low, deviations in the Nusselt number may occur. The average Nusselt number in a cross-flow over a bundle of smooth tubes can be calculated from that in a cross-flow over a single tube. For our purpose we have used the criteria equation according to [7], [8]. The heat transfer is described by the 2 parts of flow, the turbulent part and the laminar part of the flow near the walls:

$$Nu_{l,lam} = 0{,}664.\sqrt{Re_{\psi,l}}.\sqrt[3]{Pr} \qquad (10)$$

$$Nu_{l,turb.} = \frac{0{,}037.Re_{\psi,l}^{0,8}.Pr}{1+2{,}443.Re_{\psi,l}^{-0,1}.\left(Pr^{2/3}-1\right)} \quad (11)$$

Turbulent flow in pipe sets in at Re >10^4. In the transition region of Reynolds number from 2300 to 10^4 the type of flow is also influenced by the nature of inlet stream and the form of pipe inlet. Tube bundles with in-line tubes behave more like paralell chanels, which are formed by the tube rows. An expected increase in heat transfer coefficient due to the turbulence enhancement caused by the tube rows does not occur. [7]

Our aplication for hot air Ericsson-Brayton engine will use as primary heat exchanger tube heat exchanger with staggered tubes.



PICTURE N. 4. 3D model of proposed heat exchanger.

For this type of heat transfer through tube bundle we can define, according to [7], the average Nusselt number for bundle:

$$Nu_{0,bundle} = \frac{1+(n-1).fa}{n}.Nu_{l,0} \quad (12)$$

where:

$$f_{a,stag} = 1 + \frac{2}{3b} \quad (13)$$

$$Nu_{l,0} = 0{,}3 + \sqrt{Nu_{l,lam+}^2 Nu_{l,turb}^2} \quad (14)$$

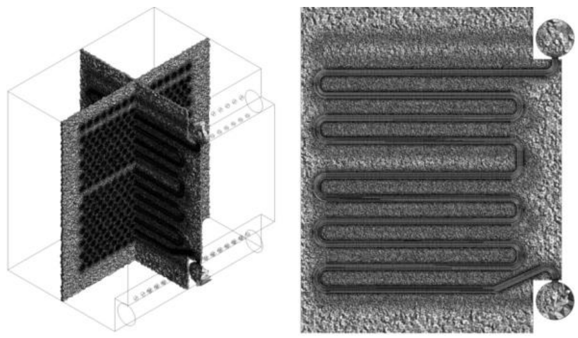
Then followed the estimation of overall coefficient of heat transfer that is depending on the Nusselt number.

$$\alpha = \frac{Nu_{bundle}.\lambda_{TM}}{l} \quad (15)$$

When we know both sides of equation, we can compare them together and estimate the overall heat transfer coefficient and the needed heat transfer surface. After this we have proceed to creation of 3D model of the exchanger. The model was in first step created with wall thickness of tubes and inlet tube. But this solution sets major requirements on computing hardware, so we have decided to create a simplified model with tubes as full material and only set the right material constants for the surfaces.

3 Heat exchanger verification using Ansys Fluent

The model for Ansys Fluent was created using 3D modeling software. Very important by the creation of model was substitute all the construction elements by simple geometrical features. [8]

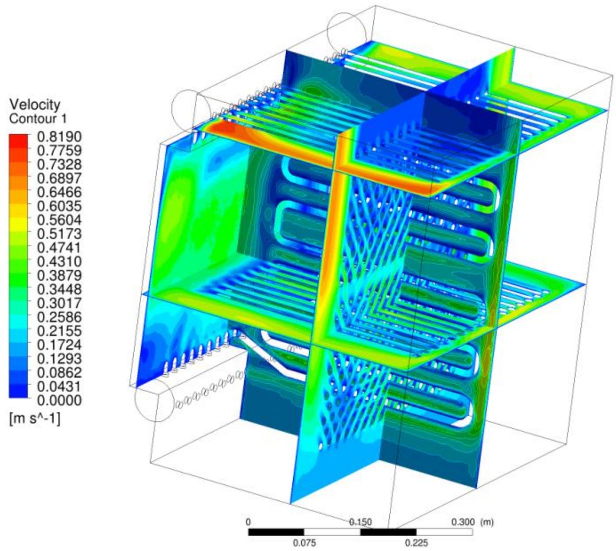


PICTURE N. 5. Generated tetrahedral mesh.

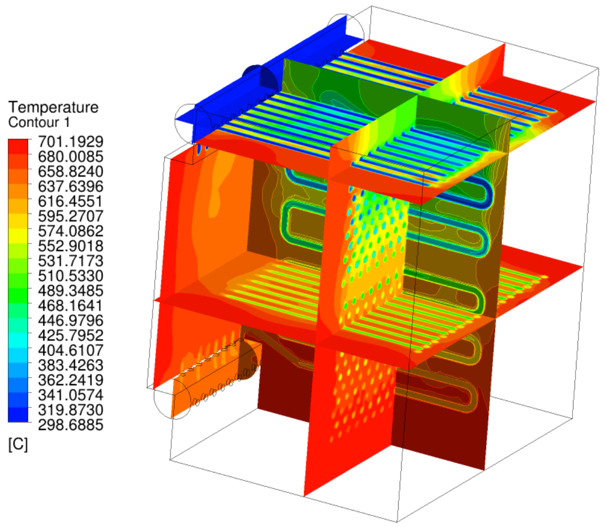
This means, that the whole exchanger was modeled as one volume with tubes as full material. The tubes have multiple collectors at inlet and outflow. No construction tolerances are reflected.

PICTURE N. 6. Detail of polyhedra mesh.

The exteriour of the heat exchanger was created by cutting out material from volume. In the first step we have used the tetrahedron mesh to fill the whole volume. Quality of generated mesh is determined by skewness of elements and by minimal orthogonal quality. Skewness by our solution was 7,1833.10^{-7}, where the lower value is representig worse quality [8]. So we have to convert the tetrahedron mesh to polyhedra mesh. Detail of generated mesh is in Picture n. 6. The model was solved with polyhedra mesh and K-ε model. The flow was predicted as turbulent. In Picture n. 7 we can see the velocity contour and in Pictre n. 8 we can see the temperature fields. Monitored were inlet and output pipes temperature, that is depending on the overall heat transfer. The current model has confirmed the mathematical model and also accuracy of chosen geometry.



PICTURE N. 7. Velocity contour in proposed heat exchanger.



PICTURE N. 8. Temperature contour in proposed heat exchanger.

Conclusion

Hot air Ericsson-Brayton engine used in cogeneration unit is a nonconventional engine, that allows us to produce electric energy by using different types of fuel, for example biomass, wood pellets etc. Heat exchanger design for hot air Ericsson-Brayton engine sets wide range of specifications. As first step we have defined the working conditions of whole unit and the needed power and temperatures for every element of this machine. We have set basic dimensions for the heat exchanger using criterion formula. With this calculation we have also verify the inlet and outlet temperatures of the exchanger. Then followed the calculation using Ansys Fluent. As next step we have to complete the construction documentation and finish all design fundamentals, so the construction and real measurements can follow.

Acknowledgments

This work is supported by "Výskum nových spôsobov premeny tepla z OZE na elektrickú energiu využitím nových progresívnych cyklov" ITMS 26220220117.

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