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THE RESEARCH OF IMPROVEMENT WAYS FOR PYROLYSIS GAS COOLING AND BLOWING PROCESSES IN PYROLYSIS GAS POWER STATIONS USING CONVENTIONAL TECHNICAL SOLUTIONS

The article is dedicated to describing the research of different ways, appliances and solutions for flammable gas supply, transportation and cooling, performed in terms of authors' PhD theses, related to pyrolysis gas production and application for electric power production. The main idea of this research is the investigation of opportunities of application of modern simple generally used technological solutions on pyrolysis gas power plants for the above mentioned units design. The research is related to different ways of pyrolysis gas cooling and also to the ways of the gas supply from gas generator to the consumer. Another goal is to create a systematic approach to the automation of pyrolysis gas production and transportation onto future pyrolysis gas powered electric power plants.

Key words: *pyrolysis gas, gas transporting, gas cooling, gas to air mixture, flammable gases*

Introduction. The production of the pyrolysis gas is just one part in a system of its application for power production. After that, it is necessary to cool down the obtained gas and also transport it to the consuming power station as soon as possible. The reason for necessity of cooling gas is that while being heated, its density has lower values and as a result the heating value of the gas decreases. [1]

The ideal option is to cool the obtained pyrolysis gas to the ambient atmospheric temperature, but this option is acceptable for stationary power plants only. For vehicles, equipped with gas generators, it will be too costly and complicated to cool down the gas to room temperature, thus, the value of +40-60°C can be accepted.

Also, when the gas generator begins its operation, it is necessary to maintain the air blowing while the gasification process just starts and the obtained mix of gases does not contain enough flammable components for the engine to consume it and maintain air blowing by itself. Sometimes, it might be needed to transport gas to a certain distance due to various reasons. Therefore, relevant fan blowers are needed to provide this transportation.

The analysis of existing research. The fan blowers themselves are not new inventions. So is the cooling system. However, their application in gas generating systems has been researched at least in 1950-s with the technologies of that era. The research below will describe different existing solutions and evaluate their applicability in modern gas generating systems. However, basic historical background of cooling and air supply units of pyrolysis gas power plants is given in authors' previous articles[2] [3].

Aim of the work. The aim of this project is to analyze the modern existing solutions for pyrolysis gas cooling, transportation and mixing with ambient air

Idea of the work. The idea of this work is to perform the preliminary design of gas cooling, transportation and air mixing units using existing details and assemblies and ensure that all these processes will occur according to the latest ecologic laws of Ukraine and the EU.

Problem statement. The old design of pyrolysis power plants will not correspond to any modern ecology laws. Those old power plants and pyrolysis powered vehicles were designed in 1950-s for the last time, using the technological achievements of that era. Nowadays, the modern materials, manufacturing technologies, chemicals, etc allow to re-design existing gas cooling, transportation and air mixing systems so that the newly built pyrolysis power plants will be eco-friendly and profitable.

Potential limits. As it was stated above, the design of pyrolysis powered vehicles limits the size and weight of gas generator and its accessories, such as gas filtering, cooling and air mixing units. However, when it comes to stationary pyrolysis power plants, there exist less limits in order to achieve the desired results.

The explanation of the idea. The first issue to be evaluated in this article, will be related to the fan blowing. Fan blowers are used during the initial burning of fuel inside gasification chamber of the gas generator and also, if needed, for the purposes of obtained gas transportation from gas generator to the consumer. Additionally, the datum thesis involves research of methods of intensifying of pyrolysis process which would also involve the application of fan blowers.

The modern 3D-printing technology allows the production of fans, having more complicated shape comparing to old ones. For the purposes of blowing, two types of fans are used – centrifugal and tangential.

Both of these types exist with 3 typical types of blades (fig.1):
a)   Straight
b)   Forward curved
c)   Backward curved

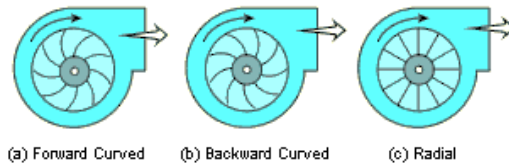(a) Forward Curved   (b) Backward Curved   (c) Radial

Fig. 1 Conventional types of centrifugal fan blowers

Additionally, it will be a good idea to research various options of S-shaped blades (fig. 2).

In order to perform calculations of typican fan design, it is required to establish initial conditions, such as required air mass flow, type & power of electric engine applied, maximum allowable RPM for the fan from designed material. Another aim of calculations is to verify whether S-shaped fan blowers would bring benefits to the designed air flow system performances.

The diagram 1, shown below, is an example of fan blower diagram. It shows the main data of a fan blower, applied onto old fan blower for ZIS-21 car. Nevertheless, it shows some main performances and tendencies of the fan blower:

– The highest total efficiency value is approximately 0.1.

– It is achieved along with the highest gasification rate, approximately equal to 110 m^3/hour.

– The highest fan efficiency involves its lowest value of RPM.

– The highest pressure difference produced by that fan was equal to 140 mm. Hg.
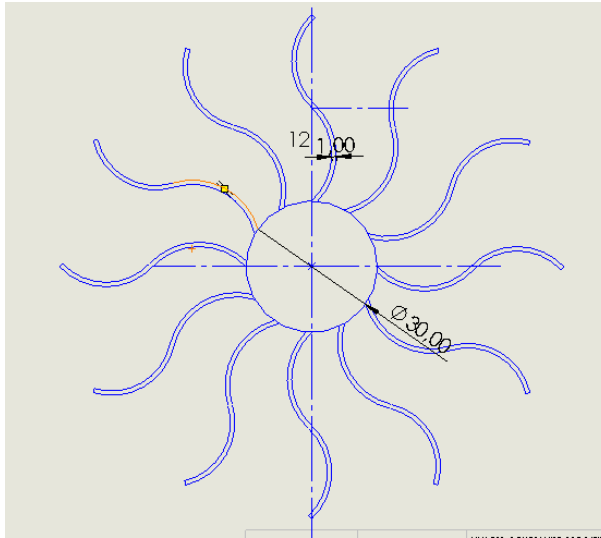
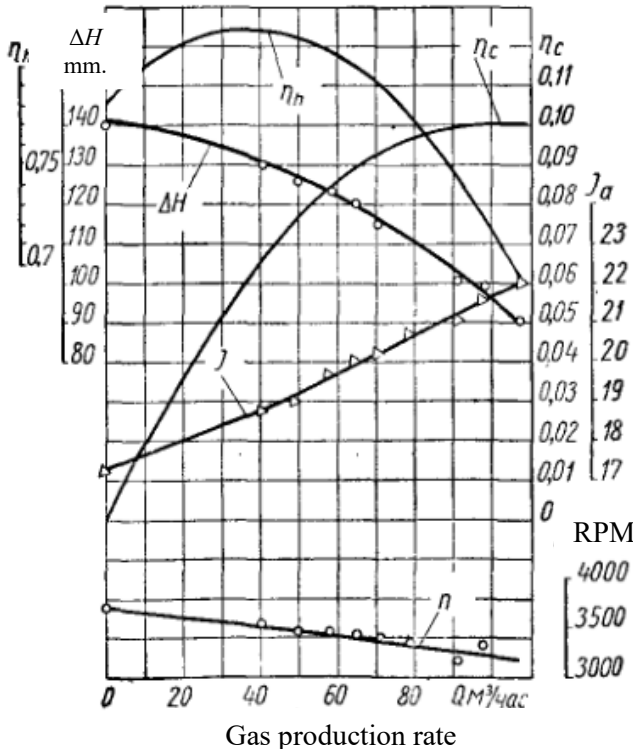Fig. 3. The example of centrifugal fan blower with S-shaped blades

Gas production rate

Diagram1: The dependence between gas productivity rate (*x*-axis) and fan blower efficiency, fan RPM, pressure difference (*y*-axis)

Another diagram 2 is vital for the datum research, since it properly demonstrates different efficiency options of fan blowers for gas transfer, depending on the place of their installation – either at the gas-air mixing unit or right after the gas generator. The diagram shows that if the fan blower is installed right after the gas generator, its productivity will be relatively higher (up to 80 m^3/hour in e.g. diagram). This means

that there will be needed less time to initially gasify the fuel. Also, it will be required to dump the initial low-quality gas either to atmosphere (which is not desired) or to certain initial gas collectors until the proper gas will be produced inside gas generator. And the main disadvantage of such installation option is that the gas cooling system, air-gas mixer and engine itself will not be properly filled with gas before engine start, which would make it harder, requiring usage of more batteries' energy at start.

The second installation option is the application of fan blower right before gas-air mixing unit has lower value of productivity (in e.g. diagram the value is approximately 50 m^3/hour). However, in this case all gas supply system will be filled with gas, which would make engine start easier to occur.
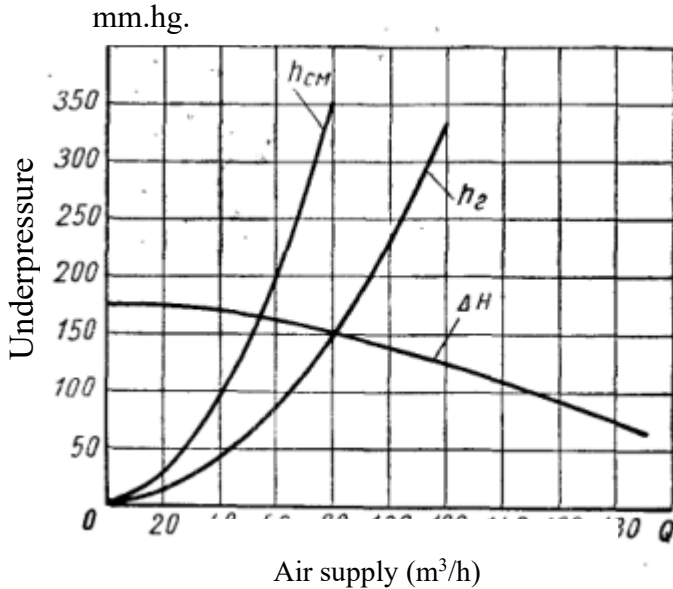

Diagram 2, showing relation between gas productivity, pressure difference in gas supply system and two options of fan blower installation: h_{CM} – in front of air-gas mixing unit and h_2 – right after gas generator

It is also obvious that the increment of fan blower efficiency leads to the increment of electric power needed to power it. This dependence is presented on the diagram 3. This diagram represents tests, performed on a fan with productivity equal to 100 m^3/h that had to blow the air for re-burning of gas generator after 1 hour of stoppage. It is clear from this diagram that with higher fan efficiency, the time to establish proper burning of gas increases and vise versa.

On the other hand, the greater efficiency leads to greater power consumption. Therefore, it is necessary to establish a certain optimum value of fan efficiency for each specific fuel. The diagram 3 also shows that the optimum efficiency values for fans, blowing gas generators with different fuels loaded, are the following:
- 80-85 m^3/hour for anthracite
- 65-70 m^3/hour for wood coal and pete coke

Therefore, it is necessary to develop similar diagram for different types of RDF. In order to calculate power consumption of the fan, the following formula is used:
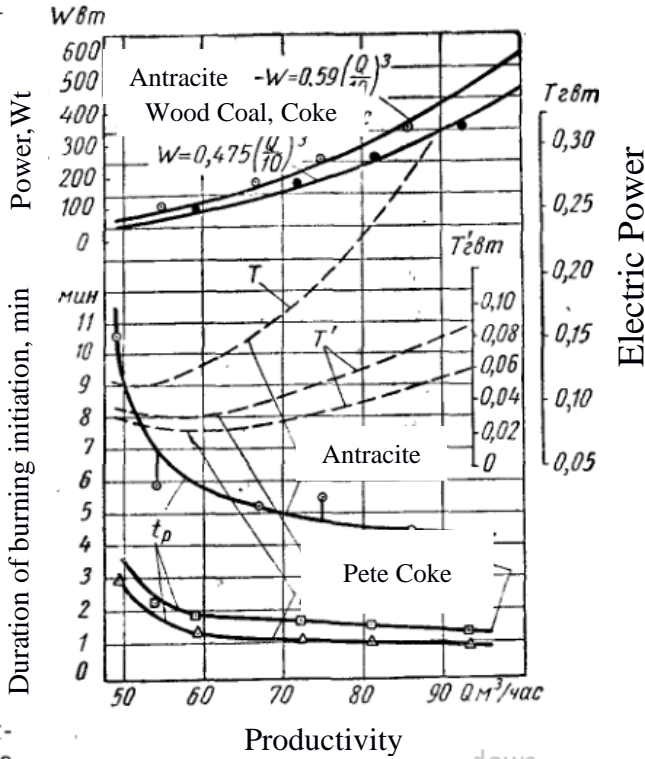
Diagram 3: The dependence between gas generator stoppage time and the amount of air needed to re-burn it again

$$W = \frac{Q\Delta P}{367\eta_C}\,(Wt)$$

$$N_R = \frac{Rv}{745}\,(h.p.)$$

In this article, authors' will use earlier the conventional vacuum cleaner fan blower of maximum 1800 Wt power [4]

It is required to calculate the pressure difference, produced by the datum fan using the next formula[5] [6]:

$$\Delta P = \frac{\gamma}{g}u^2\eta_h\,(kg/m^2)$$

$$u = \frac{\pi d n}{60}$$

where γ is specific weight of the medium (air in our case), η_h is a fan's hydraulic coefficient and u is velocity on the fan wheel's tip, calculated by formula above (fig. 4).
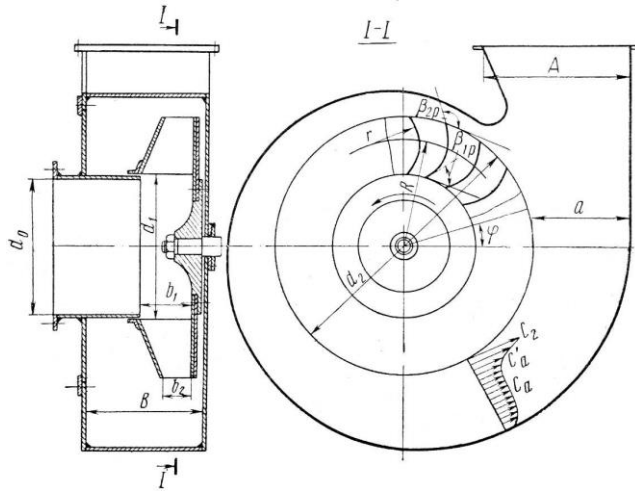
Fig. 4 The cross-section of a typical fan blower and the scheme of forces acting on its blades

Therefore, there is a need to conduct an experiment with S-bladed fans to determine their hydraulic coefficients and determine whether their application will bring any benefits.

The second issue to be evaluated in this article, will be related to the modern opportunities of gas cooling. This stage of pyrolysis gas production is highly essential, since the better the gas is cooled before entering the engine, the better flammability and heat capacity it produces. (fig.5) [7]
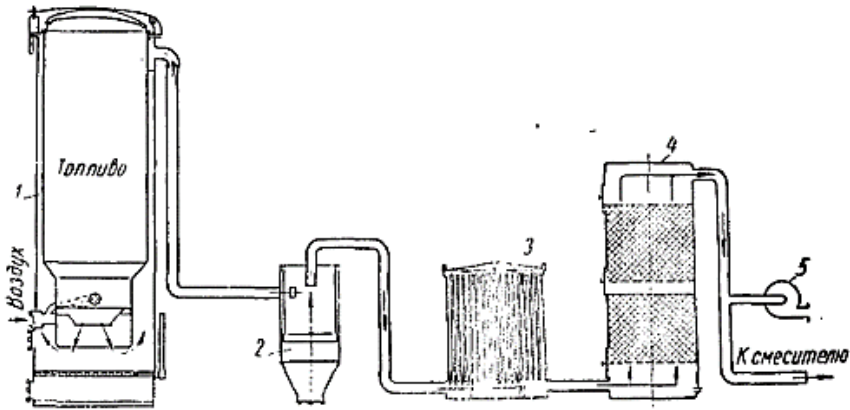

Fig. 5. Typical scheme of the gas cooling system of pyrolysis gas power plant: *1* – gas genarator; *2* – primary gas purificating unit; *3* – gas cooling unit; *4* – secondary gas cleaning unit; *5* – fan blower

In this chapter, the attention will be drawn to the gas cooling unit. The simplest approach to the creation of this device is the application of a simple barrel with water. Such a water container will be the primary cooler, but what more important – it will be a hydraulic brake for the emerging gas due to the fact that the gas itself may pop out of the RDF granules in an uncontrolled way.

However, since the water freezes in winter time, it is obviously necessary to substitute it with proper cold-resistant fluid. The simplest idea that arises is the application of

conventional automotive anti-freeze fluids. They are produced in large amounts and are easily available at any potential power plant site.

First of all, it is required to analyze the potential properties of existing automotive anti-freeze fluids. There exist 4 main types of car anti-freezes [8]:

– Conventional blue: the oldest existing anti-freeze. This is a mix of distilled water, ethylene glycol and the mix of additives. Those additives usually do not allow this type of anti-freeze to withstand temperature higher than $+108^0C$ and also they limit the service time of anti-freeze to 2-3 years maximum. This is why such anti-freeze in unacceptable for the datum project of pyrolysis power plant.

– G11 green/yellow: this is better solution of chemicals, since it already contains organic carboxylic acid. This anti-freeze has good anti-corrosive properties, since it creates thin film that covers all surfaces of heat exchanger and elongates its lifetime. However, the additives of G11 anti-freeze still have a tendency to solidify into small crystals which will lead to blockage of all tubes of heat exchanger.

– G12 red: the only disadvantage of this type of anti-freezes is that its mostly organic additives (including up to 80-90% ща earlier mentioned carboxylic acid) do not create corrosion protective film, but act on existing corrosion spots. This disadvantage can be disregarded when it comes to the application of this anti-freeze in primary gas cooling unit. This anti-freeze is perfect on heat transfer, does not crystallize and block tubes and its estimated service lifetime is equal to 5 years. Also, G12 anti-freeze has been initially designed for application in either copper or brass car radiators, which is rare in cars, but quite common at heat power plant industry.

– G13 violet: this type of anti-freezes is in worldwide production since 2012 and its main difference from all previous ones is the application of safe propylene glycol as the main anti-freeze agent instead of poisonous ethylene glycol. In all other aspects it is similar to G12 series anti-freezes. Moreover, its lifetime is not limited in case this type of anti-freeze is poured into a new cooling system.

This brief analysis allows to make the following selection of anti-freezes for designed pyrolysis power plant:

– G11 for primary gas cooling units of simple/temporary pyrolysis power plants, since due to the relatively poor performance of minor gas generators, the outgoing gas will contain higher amount of solid particles which will contaminate gas cooling tank quicker comparing to proper made stationary gas generators.

– G12 for primary gas cooling units of large gas generator power plants due to the huge amount of produced hot gas.

– G13 for any future designed heat exchangers for the power plant due to its perfect properties.

Next comes the primary design template for a heat exchanger, applied to the gas cooling unit. The applied fluid will be G13 (violet) anti-freeze and the task of heat exchanger will be to heat the water for hot water supply to households.

The final result of heat transfer calculation of the heat exchanger if the area of heat transfer, which is calculated using the following formula [9] [10]:

$$A = \frac{Q}{k \times \Delta t_{av}}$$

where k $(Wt/(m^2K))$ is the heat transfer coefficient, Δt_{av} is the average temperature difference and Q is heat load of heat exchanger.

Heat load of the heat exchanger is calculated using the following heat balance equations:

$$Q = G_1 \Delta h_1 \eta \qquad Q = G_2 \Delta h_2$$

where G_1 and G_2 are correspond to the expenditure of hot and cold heat medium respectively, Δh_1 and Δh_2 are changes of enthalpy during the heat exchange process and η is heat losses coefficient. Its values range from 0.97 to 0.99.

The changes of enthalpy during the heat exchange process are calculated using the next formula:

$$\Delta h = c_P$$

where c_P (J/(kgxK) is the average isobaric heat capacity of heat transfer medium and t' and t" are initial and final temperatures, respectively.

The heat transfer coefficient k (Wt/(m^{2}K)) is determined using the following equation:

$$k = \frac{1}{R_1 + R_2 + R_3 + \frac{1}{\alpha_1} + \frac{1}{\alpha_2}}$$

where R_1, R_2 and R_3 are thermal resistance coefficients of dirt from inner and outer sides of the heat exchanger's wall and of the wall itself.

The wall's thermal resistance coefficient R_2 is calculated using the next formula:

$$R_2 = \frac{\delta}{\lambda}$$

where λ (Wt/(mxK)) is heat transfer capacity of the wall material and δ is the wall thickness, m.

The values of R_1 and R_3 are derived from experiments. For R_1, the heat resistance coefficient of the inner part of heat exchanger, the lowest value from experimental data can be taken (since it is assumed that G13 anti-freeze will not cause any crystallization spots at any place of the designed heat exchanger) and it is equal to 0.0002. For R_3 the value is chosen to be equal to 0.00033 (this value corresponds to the appearance of the scale on the outer surface of the heat exchanger).

For the designed gas generator power plant, it is necessary to choose the materials from available stock. This concerns the materials for heat exchanger as well. One of the most popular wall thickness of the available copper tubes is 1.2 mm. This value will be used in the following calculations.

The value of heat transfer capability of copper is taken from experimental data as well and is equal to 401 Wt/(mxK). Therefore, the value of R_2 is:

$$R_2 = \frac{0.0012}{401} = 0.00000299$$

Also, it is needed to mention that α_1 and α_2 are heat irradiation coefficients and and they are calculated by the following way:

$$\alpha = \frac{q}{\Delta t}$$

where q is heat flux density and Δt is the temperature difference. The dependence between these values is depicted on the so-called Nukiyama curve. Initially, this diagram has been developed for boiling water by the Japanese scientist Shiro Nukiyama in 1930-s (fig. 6) [11]
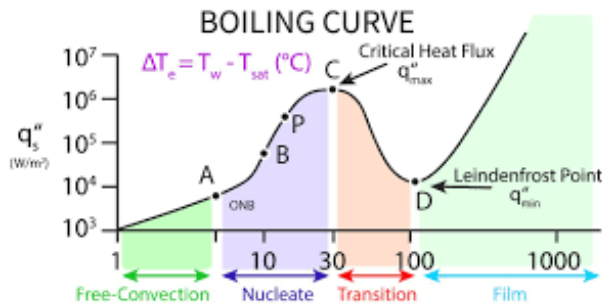

Fig. 6. Nukiyama's curve of boiling water

If briefly – this curve describes the state of boiled fluid (it was the water in Nukiyama's research) from initial free surface boiling, then – bubble boiling and eventually – the film boiling.

However, besides the above mentioned experimental curve, there exists also a formula to determine the heat flux density:

$$q = \frac{\lambda}{\delta} \frac{\pi d_m}{\varphi} \Delta t$$

where φ is the curvature coefficient, and d_m is the so-called average diameter. These values are determined by the following two formulas, respectively:

$$\varphi = \frac{d_2}{d_1} = \frac{10}{7.6} = 1.316$$

$$d_m = \frac{\sum d}{2} = 13.8$$

Therefore:

$$q = \frac{401}{1.2} \frac{\pi \times 13.8}{1.316} \times 180 = 1981566.727$$

$$\alpha_1 = \frac{1981566.727}{180} = 11008.704$$

$$\alpha_2 = \frac{1981566.727}{100} = 19815.667$$

$$k = \frac{1}{0.00000299 + 0.0002 + 0.00033 + \frac{1}{11008.704} + \frac{1}{19815.667}} \simeq 400$$

Next, we move to the calculation of c_P (J/(kgxK) - the average isobaric heat capacity of heat transfer medium. For any fluid there exists general formula for its calculation:

$$C_p = \frac{i+2}{2} R$$

$$C_p \approx \frac{\sqrt{5}}{2} \times 8.31 \approx 9.29$$

Therefore:

$$\Delta h = 9.29 \times 180 = 1672.355$$

Now, it is possible to select the expenditure of anti-freeze, running across the heat exchanger. The anti-freeze will be pumped across the heat exchanger by means of the conventional automotive pump, powered from 12V DC converter or even directly from an additional automotive generator, incorporated to the gas generator power station.

The expenditure of an average anti-freeze pump is taken to be equal to 5 m³/hour, i.e. 5.7 kg/sec. Therefore:

$$Q = G_1 \Delta h_1 \eta = 5.7 \times 1632.355 \times 0.97 = 9025.29 Wt$$

$$A = \frac{9025.29}{400 \times 180} = 0.125 m^2$$

Therefore, for spiral type heat exchanger with tubes of 10mm diameter and 1.2 mm wall thickness, the following geometric parameters can be evaluated:

1) Length of heat exchanger's pipes:

$$L = \frac{A}{\pi d}$$

2) Number of spirals of the heat exchanger:

$$n = \frac{L}{\pi d}$$

3) The height of the heat exchanger:

$$H = nd + (n-1)b + 2a$$

where a is the distance from upper to lower part of the hull.
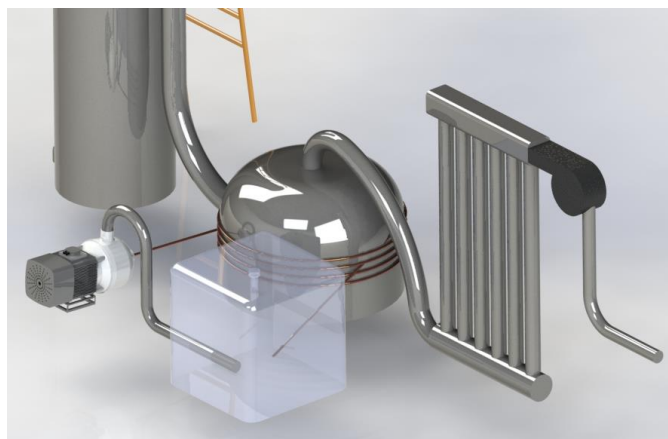
Fig. 7. The render of the designed heat exchanger

Conclusions. The calculations and calculation approaches, presented in this article, are the basis for further calculations of specific pyrolysis power plants designs. There is a variety of potential power plants designs, but these data will be useful for each single design and would allow to create sustainable pyrolysis power plants and vehicles. This research is also a basis to conduct another two experiments within the authors' PhD research:

1) The experiment to determine the hydraulic coefficients of fan blowers with S-shaped blades.

2) The experiment to determine heat resistance coefficients of different anti-freezes in order to make further calculations more accurate.

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ОБОДОВСЬКИЙ І. І., МОРОЗОВ В. С.

ДОСЛІДЖЕННЯ СПОСОБІВ ПОКРАЩЕННЯ ПРОЦЕСІВ ОХОЛОДЖЕННЯ ТА НАДДУВУ ГАЗУ В ПІРОЛІЗНИХ ГАЗОГЕНЕРАТОРНИХ УСТАНОВКАХ З ВИКОРИСТАННЯМ ЗАГАЛЬНОДОСТУПНИХ ТЕХНОЛОГІЧНИХ РІШЕНЬ

Стаття присвячена опису досліджень різноманітних рішень, технологій та пристроїв для подачі, перекачування та охолодження горючого піролізного газу в рамках дисертаційних досліджень авторів, присвячених піролізним енергетичним установкам. Основна ідея цього дослідження — дослідження можливостей використання сучасних, наявних у широкому доступі технологічних рішень для їх використання на проектованих піролізних енергетичних установках різної потужності. Дослідження присвячене розробці рішень для наддуву повітря до газогенератору та охолодження газу для раціонального використання його енергії. Найголовніша мета цієї статті — створити систематичний підхід до проектування піролізних енергетичних установок та вузлів наддуву та охолодження газу.

***Ключові слова*:** піролізний газ, транспортування газу, охолодження газу, горючі гази.

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