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Bench tests of BWC pressure free heat exchanger - part 1

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Abstract: A requirement to limit the temperature of diesel engine components results from the recommendations of the drive manufacturers as well as from the mining regulations. In order to meet these requirements it is necessary to reduce the temperature of the exhaust gases below 150 °C and in order to achieve this objective, in the exhaust system of the diesel engine various types of heat exchangers are used. The article presents the procedures and results of testing the pressure free heat exchanger for cooling the exhaust systems in underground mining machinery drives applied in hard coal mines.

1. Introduction

A limitation of exhaust gases temperature is one of the requirements for diesel engines operated in hard coal as well as metal ores and other minerals mines. During the operation of a heat machine, which is a piston diesel engine, the thermal energy is converted into mechanical energy. Unfortunately, only a part of the fed thermal energy is converted into work, while a significant part is emitted to the environment [3].

Problems related to cooling of exhaust gases in diesel engines used in hard coal mines and a development of the devices designed for this purpose are discussed in the article [5].

The article presents the assumptions, testing procedure and results of testing the pressure-free heat exchanger (PFHE) on the test stand at KOMAG in Gliwice.

2. Reason for undertaking a realization of a pressure free heat exchanger design

Two solutions, i.e. wet scrubbers and dry heat exchangers, are used to cool exhaust gases from diesel engines operating in underground workings of hard coal mines. In the wet scrubbers, the stream of diesel exhaust gases is directed to the box filled with water. The gases, flowing through water, transfer a part of heat to water and the resulting mixture of exhaust gases, steam and water drops are further directed to the next part of the exhaust system and then to the atmosphere. In the dry heat exchanger the exhaust gases are directed to a chamber made of the pipe system in which cooling agent circulates. Heat of exhaust gases is transferred to the cooling agent through the pipes wall. The wet scrubber, despite its better efficiency in cooling the exhaust gases, has a big disadvantage of a continuous loss of water in the cooling chamber.

The water is partly transferred into a steam and flows out together with gases and partly it flows out as small water drops entrained by exhaust gases. That is why water has to be periodically refilled in

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the cooling box. Depending on an intensity of using the diesel engine, water should be refilled once or twice per shift.

Users of diesel engines with wet scrubbers draw attention to a necessity of limiting the above mentioned water refilling process. This process disorganizes an operation of the machine with a diesel drive and water torn out from the exhaust system is wasted as it cools down the gases only partially.

KOMAG specialists have undertaken many research activities aiming at a limitation of volume of water torn from the wet scrubber by e.g. changing the scrubber box design and introducing a spiral outlet with bouncing metal sheets [1].

Recently, a project on a pressure free heat exchanger was realized, an experimental version of such a device was developed [6] and the stand tests of it were conducted [4].

A pressure free heat exchanger is a device combining the advantages of a wet scrubber and of a dry heat exchanger. In this device, the exhaust gases flow in the system of pipes immersed in water, transferring a part of heat to water causing its evaporation. The outlet of exhaust gases from the pipes system is placed over the water surface, where the gases combine with steam and flow to the outlet duct. The gases are cooled down during the flow through the outlet duct. An efficiency of cooling the exhaust gases is nearly the same as the cooling efficiency of a wet scrubber but in this case the water drops are not torn out from the system .

In Figure 1 a sketch of a pressure free heat exchanger (PFHE) is presented.

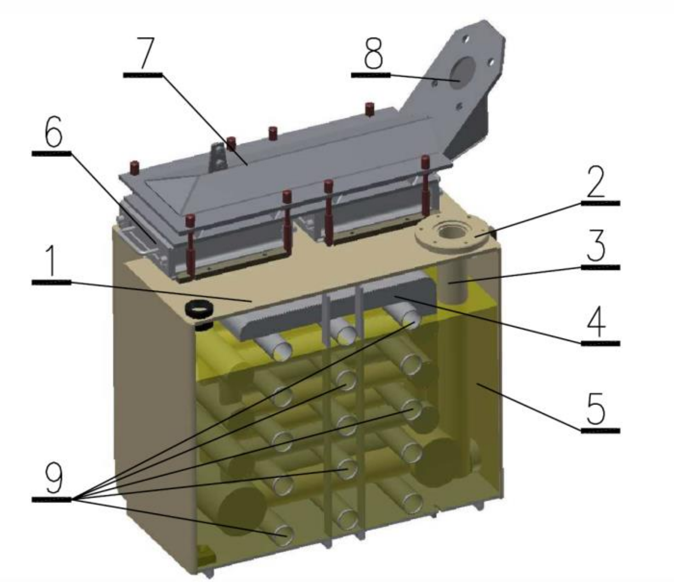

Figure 1. Pressure free heat exchanger: 1 – heat exchanger box, 2 – connection of the exhaust gases outlet, 3 – exhaust gases outlet duct, 4 – labyrinth of cooling pipes, 5 – water, 6 – flame arrester, 7 – exhaust manifold, 8 – connection of spark arrester, 9 – strengthening pipes [own source].

3. Testing assumptions (objectives)

A verification of the pressure free heat exchanger efficiency i.e. an ability of cooling the exhaust gases and transferring the heat to the atmosphere was the main tests objective. A comparison of the PFHE efficiency and of the wet scrubber according to KOMAG design was the second tests objective. During the designing process it was assumed that a new design was to be compatible with the design of wet scrubbers used in underground locomotives designed at KOMAG to be replaced by PFHE during an overhaul if the users wanted to do this.

It was assumed that an ability of cooling the exhaust gases and transferring the heat to the atmosphere would be assessed basing on temperature measurements at selected points of diesel drive exhaust system. The assumption is in line with one of the requirements put upon diesel drives, specifying the maximum unit surface temperature of the diesel drive.

4. Testing stand and testing object

The tests were started on the test stand designed for testing KOMAG diesel drives with a heat exchanger in a form of a wet scrubber to realize the second testing objective (a comparison of PFHE efficiency with the exhaust gases wet scrubber according to KOMAG solution).

It was assumed that the tests of PFHE would be conducted on a modernized stand for testing diesel drives.

The modernization consisted in an adaptation of the stand for an installation of the PFHE and equipping it with additional temperature sensors used for an assessment of the PFHE efficiency.

In Figure 2 a model of the test stand for diesel drives with the installed PFHE is shown.

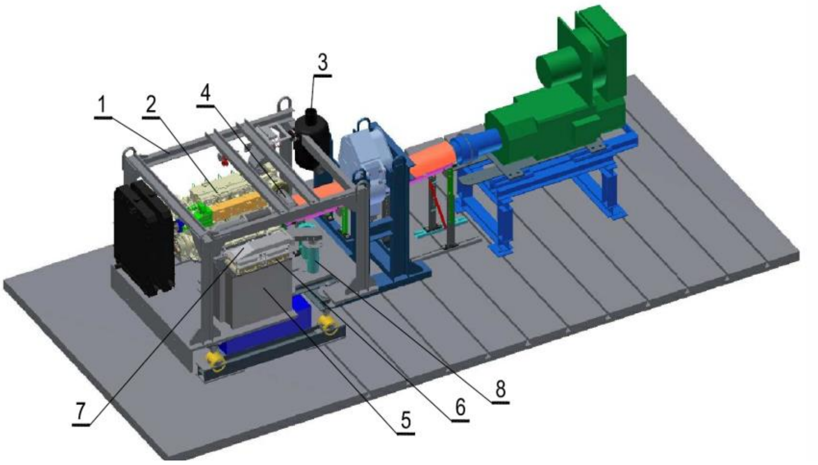

Figure 2. Model of the test stand for diesel drives: 1 – fixing frame; 2 – diesel engine; 3 – inlet system; 4 – exhaust gases outlet duct; 5 – pressure free heat exchanger (PFHE); 6 – flame arrester; 7 – exhaust manifold; 8 – spark arrester or exhaust gases outlet duct [own source].

D5AT diesel engine of 81 kW power was installed on the test stand. The engine characteristics is given in Fig.3.

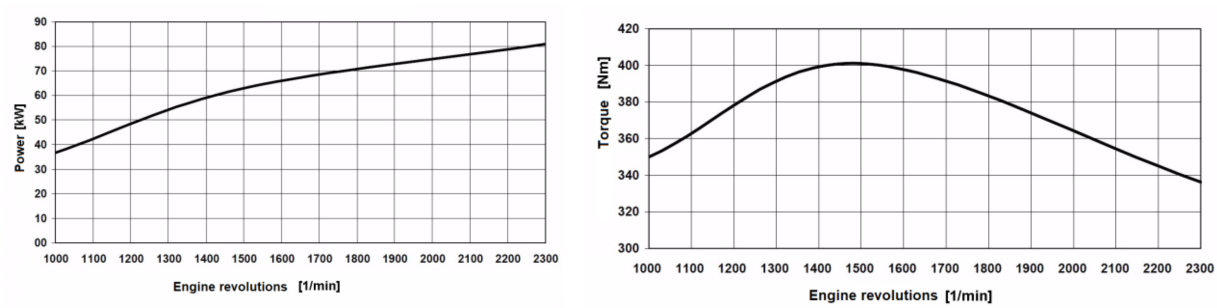

Figure 3. Characteristics of D5AT engine operation.

An experimental version of the pressure free heat exchanger PFHE was the testing object. It differs from the commercial version as it is not in the explosion-proof design and it is manufactured as an easy-to-be-disassembled box without any additional enhancements. Such a solution resulted from an intension to test two versions of cooling pipes labyrinth (see Fig. 1), hereinafter called heat exchangers. These two versions differ by the parameters of used cooling pipes. In Figure 4 the heat exchanger with pipes d=44.5 mm is shown.

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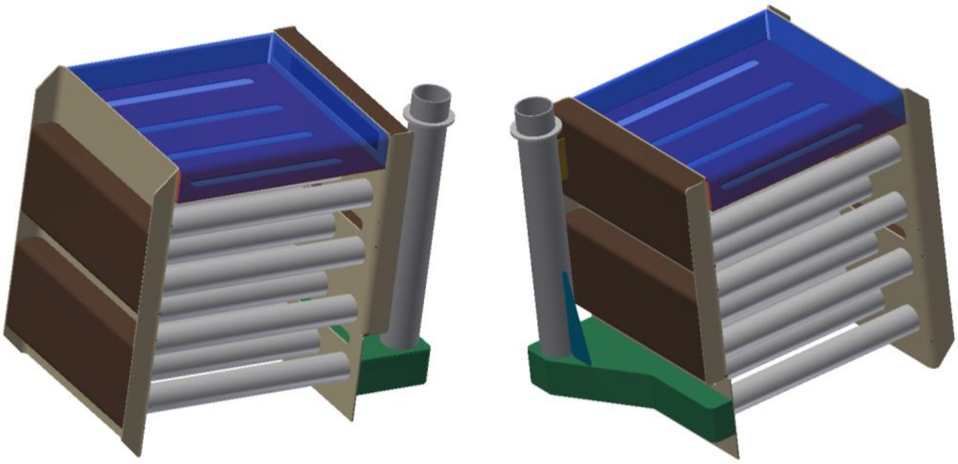
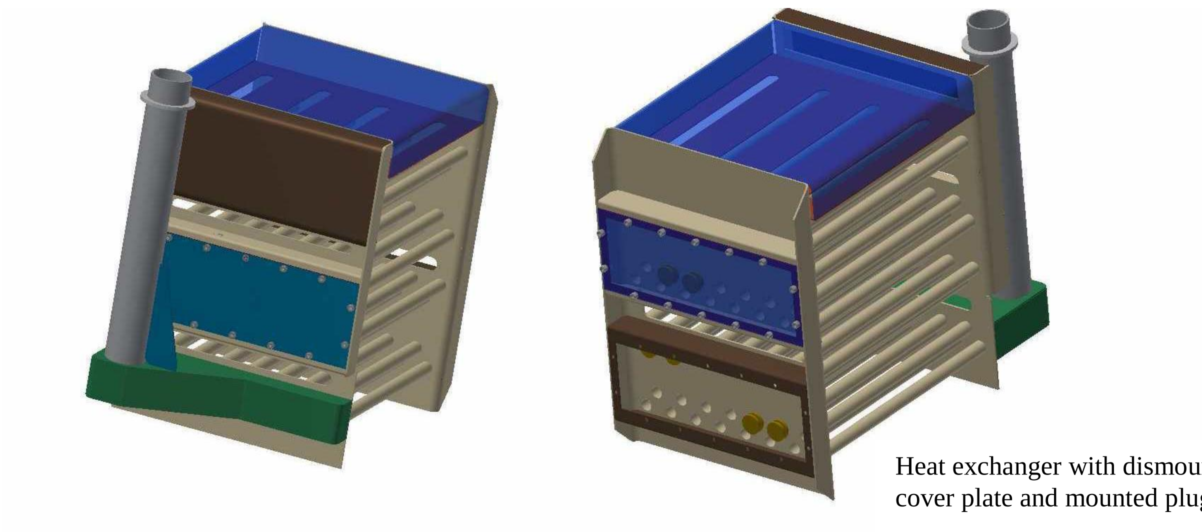


Figure 4. Heat exchanger d=44.5 mm.

For the second heat exchanger version with pipes d=20 mm, the following two testing cycles were planned: the standard one as for the heat exchanger 44.5 mm and the cycle modelling the partial clogging of the cooling pipes. The effect of partial clogging was obtained by blocking a part of the pipes using special plugs. The heat exchanger d=20 is shown in Fig. 5.



Heat exchanger with dismounted cover plate and mounted plugs

Figure 5. Heat exchanger d=20 mm.

Testing procedure

The PFHE efficiency tests consisted in measuring and recording temperatures at specific points of the exhaust gas outlet system, as well as in measuring the water level in the heat exchanger.
A list of measurement points is given in Table 1.

Table 1. List of temperature measurement points and cooling water surface level.

Symbol	Description	Fixation
P1	In the stream of gases flowing out of the turbocharger	socket M12x1,5
P2	Surface of the outlet duct behind the turbocharger	socket M12x1,5
P3	In the stream of gases flowing into the heat exchanger	socket M8
P4	Surface of the outlet duct before the heat exchanger	glued sensor
P5 and 5a	The external surface of the heat exchanger box	glued sensor
P6a and P6b	Water temperature inside the heat exchanger box	2 sockets M12x1,5
P7a P7b	The temperature of the mixture of exhaust gas and steam at the outlet of the heat exchanger	2 sockets M12x1,5
P8a and P8b	The front surface of flame arresters	glued sensor
P9	Surface of the spark arrestor (if present)	glued sensor
P10	Surface of the exhaust manifold (behind arresters)	glued sensor
P11	Surface of the outlet duct	glued sensor
P12	Exhaust gases outlet	socket M12x1,5

Figure 6 shows an arrangement of measuring points on the tested object.

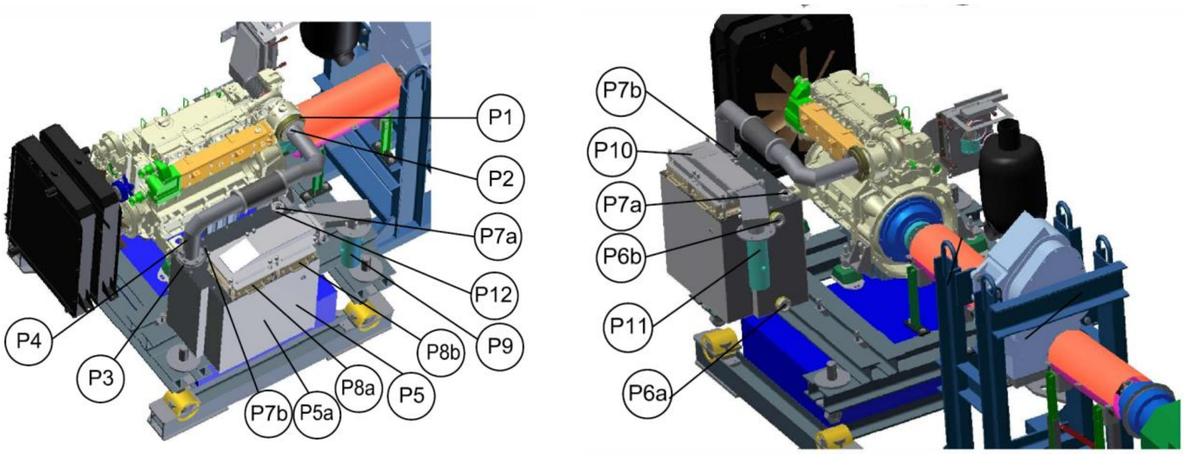


Figure 6. Places of temperature sensors installation.

Due to the fact that the authors intended to compare the results of the pressure free heat exchanger tests with the test results of the currently used wet exhaust gas scrubbers, the testing process was divided into four stages:

Stage1 Exhaust gas tests (temperature measurements) with built-in wet scrubber.
Stage2 Exhaust gas tests (temperature measurements) with built-in PFHE heat exchanger with d=20 pipe system.
Stage3 Exhaust gas tests (temperature measurements) with built-in PFHE heat exchanger with d=44.5 pipe system.
Stage4 Exhaust gas tests (temperature measurements) with built-in PFHE heat exchanger with d=20 pipe system, with partially blocked exhaust gas flow.

It was assumed that the measurements would be taken for the operating points of the diesel engine (engine + engine test bench) as in Table 2.

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Table 2. List of operating points of the diesel engine.

Operating point	Revolutions [1/min]	Torque [Nm]	Engine load [kW] *	Operating time [min]
M1	Engine idling (800)	-	-	30
M2	1500	191	30	50
M3	1500	287	45	25
M4	1500	350	55	30
M5	1500	363[1]	57	30
M6	1500	350	55	25
M7	1500	287	45	25

[1] maximum torque

Before starting the tests, each of the tested heat exchangers was filled with water. For a wet scrubber it was 141 l, while for the PFHE it was 103 l. The result of the exhaust gas flow through the heat exchanger was water rushing and pressure increase in it. This phenomenon occurred especially in the case of a wet scrubber. For this reason, to measure the water level correctly, after the end of the measuring cycle at each operating point, the diesel engine was switched off.

The time of conducting measurements at each operating point resulted from a stabilization of temperatures for the first tested configuration (wet scrubber).

5. Measurement results

Temperature measurements in the following points: P1, P3, P5, P8, P10, P11 and P12, are important for a verification of the PFHE correct operation.

In Table 3 the results of maximum temperature measurements in the selected points at testing each version of the device in each operational point are listed.

The symbols are as follows:
MP- wet scrubber of exhaust gases,
PFHE 44.5- pressure free heat exchanger with pipes d=44.5 mm,
PFHE 20- pressure free heat exchanger with pipes d=20 mm,
PFHE 20z- pressure free heat exchanger with pipes d=20 mm,
with partially blocked exhaust gases flow.

Table 3. Maximum temperatures in each mode of operation.

Operating point	Temperature of P1 measuring point [°C]				Temperature of P3 measuring point [°C]			
	MP	PFHE 44,5	PFHE 20	PFHE 20z	MP	PFHE 44,5	PFHE 20	PFHE 20z
M1	101.9	106.0	108.3	107.5	74.8	75.3	78.1	77.7
M2	304.3	312.7	306.6	316.2	229.0	234.3	233.7	243.8
M3	396.7	394.9	398.2	405.7	299.2	302.6	304.8	314.1
M4	462.2	460.6	461.4	470.0	351.5	358.9	363.0	371.9
M5	472.2	478.7	474.8	487.6	363.8	377.8	374.0	390.6
M6	465.5	463.8	470.3	480.3	358.7	368.2	378.0	388.2
M7	406.9	404.3	406.1	414.1	315.4	316.1	321.2	329.0

Operating point	Temperature of P5 measuring point [°C]				Temperature of P5a measuring point [°C]			
	MP	PFHE 44,5	PFHE 20	PFHE 20z	MP	PFHE 44,5	PFHE 20	PFHE 20z
M1	25.4	25.8	26.3	23.6	-	-	26.5	23.5
M2	55.2	77.4	80.9	82.5	-	-	72.9	75.4
M3	60.9	93.9	98.9	98.3	-	-	89.8	91.5
M4	64.4	98.9	99.3	98.6	-	-	104.1	107.0
M5	64.8	97.5	99.1	98.3	-	-	115.9	130.0
M6	64.0	119.5	115.2	120.3	0.0	0.0	140.2	147.7
M7	64.5	122.3	128.3	135.1	-	138.6	138.6	145.0

Operating point	Temperature of 8a measuring point [°C]				Temperature of 8b measuring point [°C]			
	MP	PFHE 44.5	PFHE 20	PFHE 20z	MP	PFHE 44.5	PFHE 20	PFHE 20z
M1	22.3	22.0	22.9	20.8	22.6	22.4	23.3	20.3
M2	51.8	62.2	54.8	57.6	51.7	67.2	59.2	62.9
M3	55.8	80.1	71.4	72.9	56.9	84.5	77.0	79.0
M4	58.6	99.1	86.1	88.3	60.4	104.1	91.8	95.8
M5	61.1	113.9	95.4	102.1	61.2	120.1	101.3	110.6
M6	66.6	124.4	115.8	120.3	71.7	132.2	122.8	131.1
M7	82.8	126.9	117.3	121.2	90.8	131.2	124.1	131.1

Operating point	Temperature of P10 measuring point [°C]				Temperature of P11 measuring point [°C]			
	MP	PFHE 44.5	PFHE 20	PFHE 20z	MP	PFHE 44.5	PFHE 20	PFHE 20z
M1	24.0	23.9	24.5	22.0	23.4	23.8	24.8	22.1
M2	54.3	61.9	54.9	53.8	54.1	76.2	68.3	71.0
M3	60.3	77.0	71.0	72.3	59.8	94.6	85.3	86.5
M4	64.5	94.7	82.4	86.4	63.1	116.6	100.1	104.4
M5	65.1	105.3	91.0	98.9	63.7	130.7	108.9	121.6
M6	65.9	118.8	111.4	117.5	92.5	145.9	133.1	141.5
M7	84.8	114.1	111.1	116.4	107.3	139.6	133.0	139.6

Operating point	Temperature of P12 measuring point [°C]				Ambient temperature [°C]			
	MP	PFHE 44.5	PFHE 20	PFHE 20z	MP	PFHE 44.5	PFHE 20	PFHE 20z
M1	23.8	23.9	24.4	21.9	19.6	17.5	19.0	18.8
M2	52.9	71.9	64.5	67.0	20.8	19.3	19.4	19.0
M3	58.5	88.4	79.4	80.7	20.7	19.8	19.4	19.7
M4	62.3	108.5	93.0	96.8	20.8	20.5	20.3	19.9
M5	62.9	121.8	101.8	112.2	20.5	20.8	20.3	20.7
M6	85.5	135.8	124.8	131.5	20.6	19.8	20.3	21.2
M7	100.2	130.0	123.5	128.9	20.6	19.2	20.4	21.4

Table 4. Water level in the heat exchanger at the end of operation in each operating point.

Operating point	Water level in the heat exchanger [cm]			
	MP	PFHE 44,5	PFHE 20	PFHE 20z
Before test	50	45	45	45
M1	37	45	45	45
M2	25.5	42.5	42.5	42.5
M3	22	39	40	39.5
M4	15.5	34	33.5	32.8
M5	[1)]	27	27.5	26.5
M6	[1)]	24	22	22
M7	[1)]	21	18	18

[1)] – water level below the drain plug (< 10 cm)

In Figures 1-5, temperature changes in the selected points versus diesel engine load are shown. Sample photos, made by thermovision camera, imaging the temperature distribution on the heat exchanger are given in Figure 7.

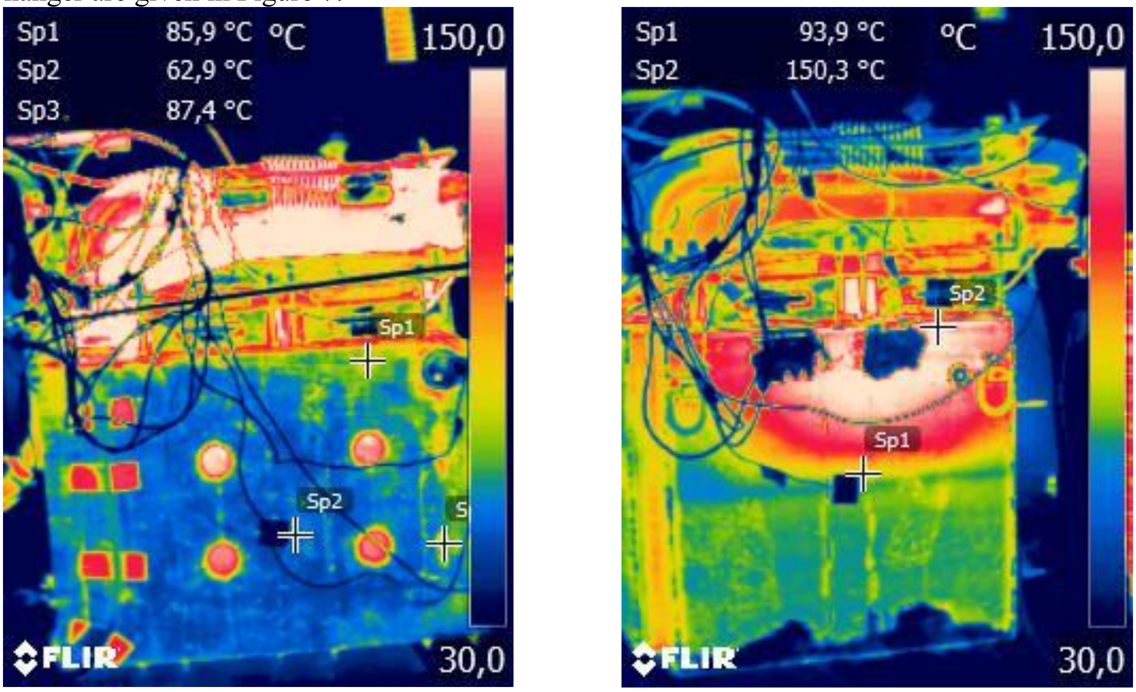

Figure 7. Thermograms of heat exchangers after the cycle completion in M5 operating point. Heat exchanger MP – on the left; pressure free heat exchanger PFHE40 – on the right

As it can be observed from the tests assumptions, relating to the diesel engine operating points, the authors planned to increase load to the diesel engine gradually (Table 2) and then to reduce it. The result of such an action can be observed as changes in temperature at each measurement point.

The temperature of exhaust gases from the exhaust manifold increases with an increase of load to the engine as it is presented in Figure 1. It is understandable, that to keep the assumed revolutions (1500 rpm) at increased torque, more fuel and air has to be fed and then converted to more mechanical energy (torque) and thermal energy which causes an increase of the exhaust gases temperature. Together with a reduction of load to the engine, the temperature of exhaust gases decreases. In Figures 8 and 9, a curve of exhaust gases temperature, when the torque decreases (reduction of load) overlaps the temperature increase curve during the torque increase (load increase). The situation of temperature changes in other selected points of the exhaust system, can be observed e.g. in Figures 10, 11 and 12.

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After a reduction of the engine load from the boundary value, the temperature drop curve has a different shape than the temperature increase curve. There is a hysteresis phenomenon. While the temperature of the exhaust gases decreases significantly, when the engine load is reduced, the surface temperature of the exhaust system components decreases more slowly, and in the case of a wet scrubber the temperature of gases increases for the engine load range.

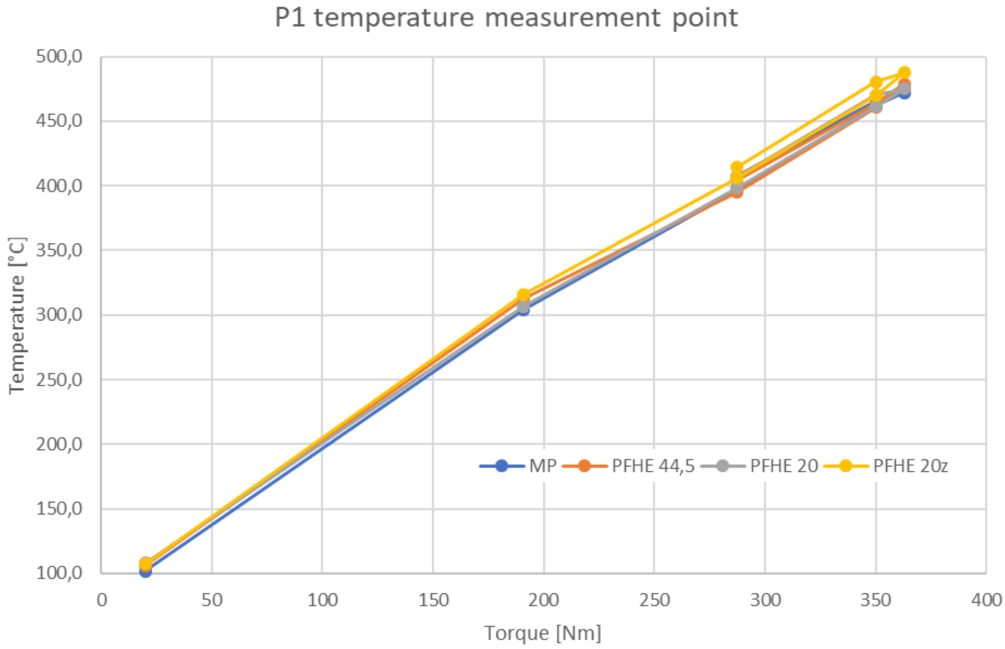

Figure 8. Maximum temperatures of exhaust gases in each operating point in P1 measuring point (turbocharger outlet).

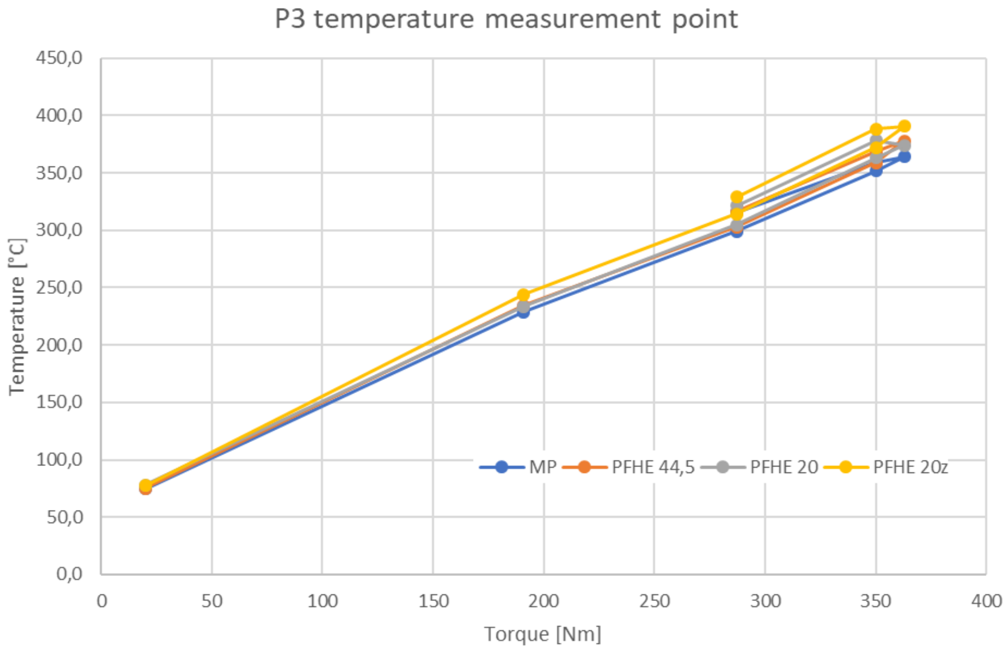

Figure 9. Maximum temperatures of exhaust gases in each operating point in P3 measuring point (exhaust gases temperature on the heat exchanger inlet).

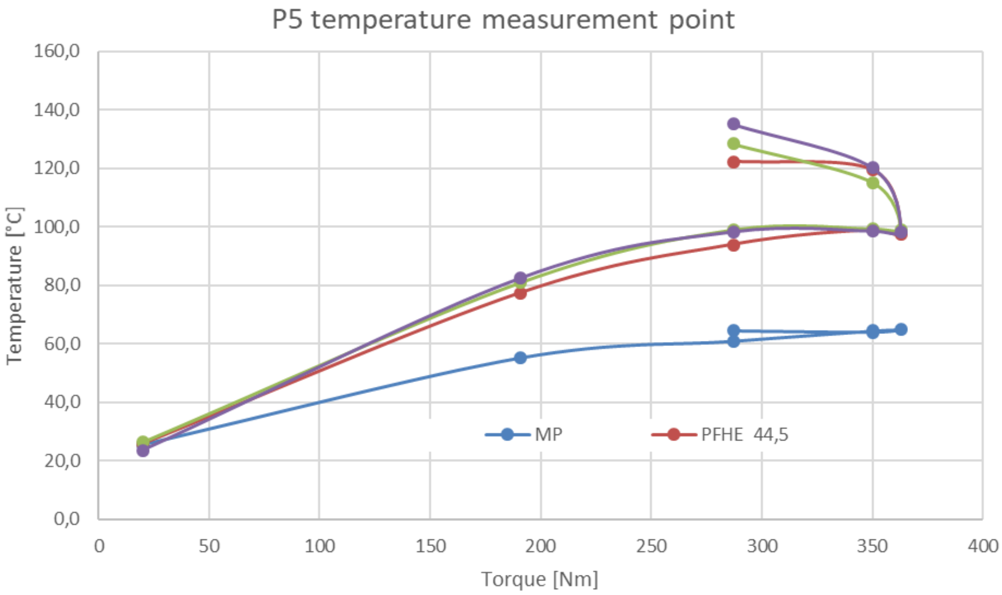

Figure 10. Maximum temperatures of exhaust gases in each operating point in P5 measuring point (external surface of heat exchanger box at half of its height).

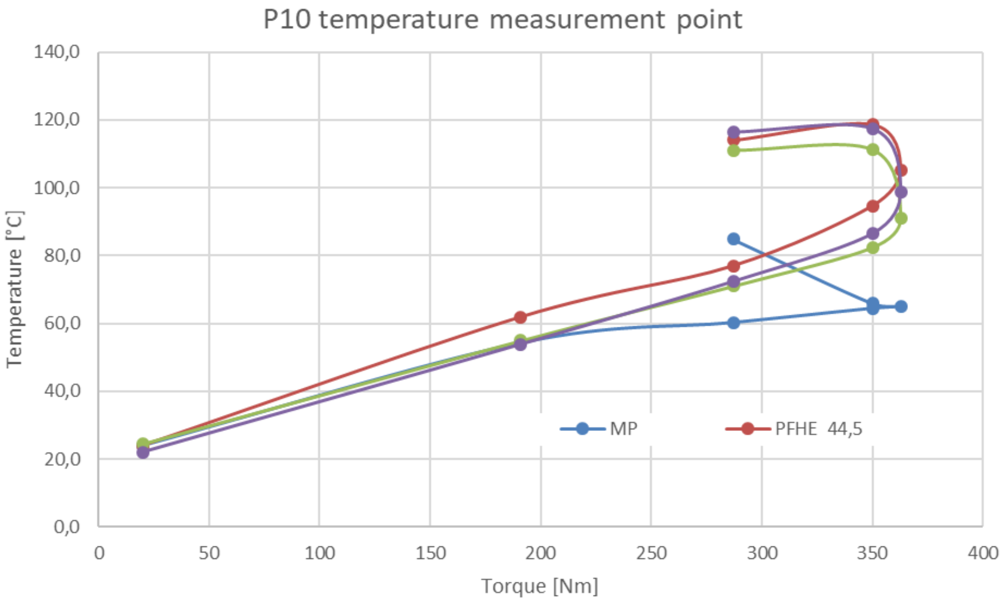

Figure 11. Maximum temperatures of exhaust gases in each operating point in P10 measuring point (surface of exhaust manifold installed on the heat exchanger).

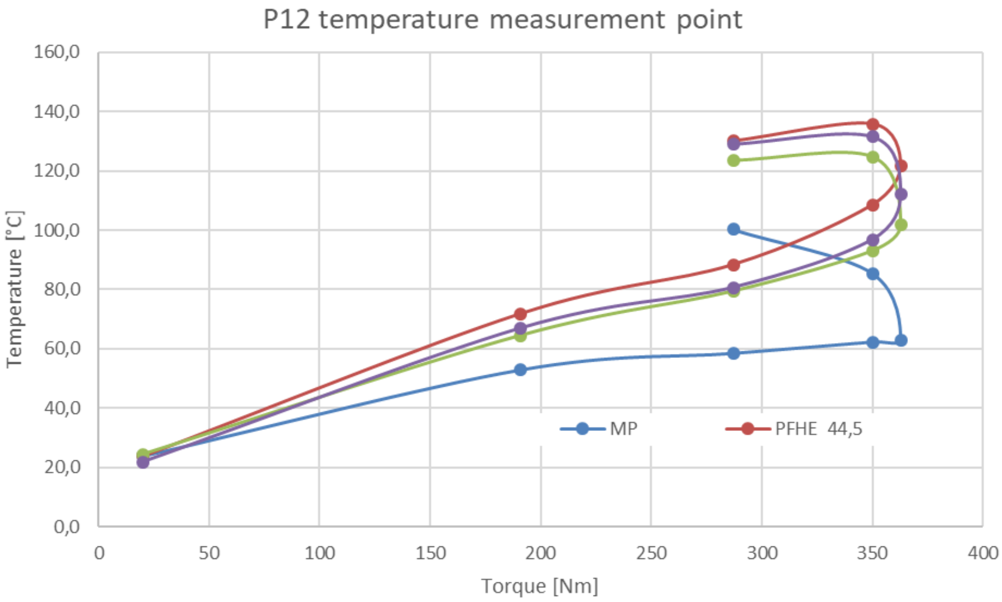

Figure 12. Maximum temperatures in each operating point in P12 measuring point (exhaust gases outlet).

That results from the water loss in the heat exchanger, reducing the efficiency of heat transfer from exhaust gases. Additionally, these systems have the specified heat capacity and the heat, cumulated during the engine operation with the highest load, is emitted to the atmosphere after a reduction in the heat amount generated by a diesel engine. It can be assumed that when the load to the engine is reduced further and after its longer operation, the systems will be cooled and the curves, representing temperature increase and drop connect and the hysteresis loop closes.

6. Conclusions

Testing the PFHE confirmed its high efficiency in cooling the exhaust gases from the engine of maximum power 81 kW. An elimination of water burst during the diesel engine operation as well as significantly lower water consumptions are the main advantages of the PFHE design. A wet scrubber (MP) has a better efficiency, among others, as it is bigger than PFHE – an initial water volume in the wet scrubber is about 1.37 bigger than in the PFHE.

Over the 3-hour engine operational cycle with load bigger than 50% of the maximum torque, in each tested heat exchanger, enabled to cool the exhaust gases below 150°C.

During the tests it was observed that the temperature of the PFHE box external surface was higher than the temperature of the wet scrubber box. However, it happened that the surface temperature of the PFHE exceeded the acceptable temperature of 150°C, but it should be stated that it was an experimental solution. The heat transfer coefficient of the material, used in the tested PFHE, was about 50 in relation to the coefficient 10 of the wet scrubber what explains the surface temperature.

During a normal operation of mine mobile machines, equipped with a diesel drive, a type of a load cycle, as in the test, does not occur [2]. Thus it can be assumed that the PFHE even as a design under-testing should meet the requirements regarding the maximum accepted surface temperature of 150 °C.

After about 3 hours of the engine operation, the wet scrubber was almost completely emptied from water, but the PFHE after 4 hours of engine operation lost 60% of water.

A cooling intensity of the PFHE can be increased by use of additional external cooling system of the cooling system box.

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