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CO2 emission standards as a challenge for the thermal activation of combustion chambers in internal combustion engines

Einhaltung der CO2-Emissionsnormen als Herausforderung für eine thermische Aktivierung der Verbrennungskammern in Verbrennungsmotoren

Abstract

Degradation of the environment, followed by laws and public opinion set requirements for the automotive industry that manufacturers judge to be unrealistic. CO2 emissions standards that have been in force since 2020 are a measure of these requirements. However, meeting them may be feasible by using the latest research achievements related to the application of active thermal layers in combustion chambers and limiting their external cooling. The paper presents the results of preliminary theoretical work carried out at the Department of Automotive Engineering of the Wroclaw University of Science and Technology in Poland together with the Engineering Office of Munich (IBS in Germany).
The assumptions of the strategy of functioning of active thermal chambers, the applied calculation model and the obtained structure of energy flows were presented. The theoretical analysis concerned the engine BMW 2.0 twin-turbo diesel engine. Improvements of nearly 40% CO2 reduction could be simulated in theoretical investigations. Experimentally validation on series engine has to be done in next time.

Kurzfassung

Die Umweltverschlechterung und mit diesem Problem verbundene Gesetze und öffentliche Meinungen stellen an die Autoindustrie Anforderungen, die sie für unrealistisch hält. Das Maß für diese Anforderungen sind die CO2-Emissionsnormen, die seit dem Jahr 2020 verbindlich sind. Eine Einhaltung dieser Emissionsnormen kann jedoch realisiert werden, indem neueste wissenschaftliche Erkenntnisse ausgenutzt werden, die mit dem Aufbringen thermisch aktiver Schichten in Verbrennungskammern und einer Begrenzung ihrer Außenkühlung verbunden sind. In dem Vortrag werden Ergebnisse von durchgeführten theoretischen Vorarbeiten vorgestellt, die im Lehrstuhl für Fahrzeugtechnik der TU Breslau und bei IBS München ausgeführt wurden und werden. Die Annahmen der Strategie für Anwendung der aktiven Wärmekammern, das angewandte Berechnungsmodell und die erhaltene Energieflussstruktur wurden vorgestellt. Die theoretische Analyse betraf den Dieselmotor mit zwei Turboladern BMW 2.0. Die Ergebnisse sagen voraus, dass die CO2-Emissionen sogar um fast 40 % verringert werden können. Die experimentelle Validierung der erzielten Ergebnisse ist beim nächsten Mal mit einem Standardmotor durchzuführen.

Introduction

The reactions of industry, politics and analysts towards CO2 emission standards and especially those binding since 2020 in the EU are connected by helplessness in the face of contradictions between civilization development and ecological threat, because it is inevitable to choose between a mobility disaster and an environmental disaster. This is reflected in the diagram developed by ICCT (Fig. 1) indicating historical changes in CO2 emissions as well as average emission values for the fleets of manufacturers of various brands of passenger vehicles - Fig. 2.

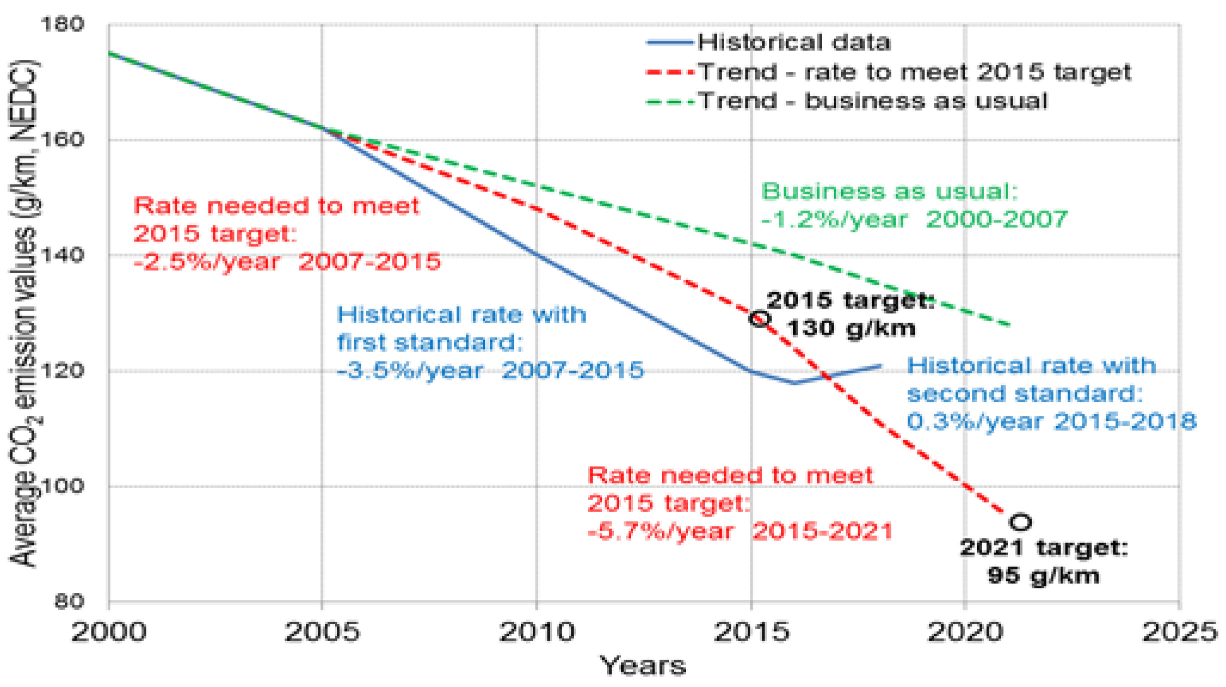

Fig. 1. Historical average CO2 emission values, targets, and annual reduction rates of new passenger cars in the European Union [1]

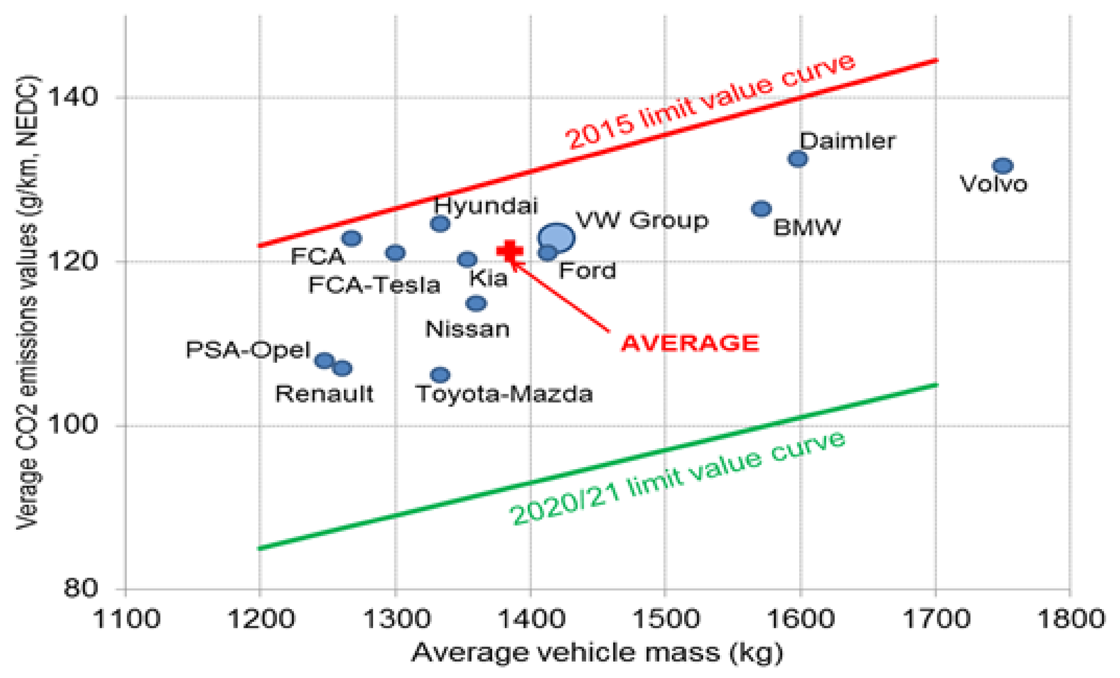

Fig. 2. Performance of top-selling EU passenger car manufacturers in 2018 compared to 2015 and 2020/2021 emission target compliance curves [1]

The various tactics proposed in the method of calculating the emission indicators are expressions of this helplessness, because according to emission standards, e.g. in the EU, it does not matter for which car brands and in what mathematical way the CO2 emissions of the manufacturer's fleet are calculated. In addition to combining brands, it can be advantageously used, e.g., deliberate reduction of the lifetime of electric cars to be able to sell them more often and increase their number in the bill on the market. Additionally, rebate and facilitation systems are being developed, e.g. in excluding the most „fuel-eating" brands from the balance sheet and government subsidies dedicated to specific options of the producer.
As a result of the game between industry, politics and the market, mobility is also becoming a hybrid, connecting the combustion and electric sides - either in the form of hybrid electric and diesel-powered vehicles or in the form of a structure in which the user wants to have two vehicles - combustion and electric one, while electric is attractively subsidized and tax-favored. The customer accepting all these financial discounts uses the electric drive depending on its convenience, the lifetime of the batteries and the condition of the infrastructure. On the other hand, the customer of a internal combustion drive after paying the ecological penalty is already using its properties with a „clear conscience".
Maybe this system saves the economic balance of producers and the image of politicians, but it does not help the environment, because it cannot be covered by the fact that the automotive industry, despite the stunning development, could not propose a realistic concept of a piston internal combustion engine, still the best possible, but still not using fully energy contained in fuel.
This article touches just standard internal combustion engine and is a continuation and development of the previous publication of the authors [2].
The leading parameter of that publication was the specific fuel consumption in internal combustion piston engines and analysis of the possibility of its reduction by more effective than in current state of the art use of heat obtained from fuel in the combustion chamber. At that time, the concept of active combustion chamber (AKS) was introduced, which the brief description is included below in this publication.
However, the leading parameter of this publication is CO2 emissions in road traffic of vehicle powered by internal combustion engine and analysis of the possibility of its reduction.

Problem description - buffering of the heat portion

In the field of known combustion chamber systems, the automotive industry has certainly already tested their potential many times.
The analysis of energy flows in the basic structures of combustion chambers and their verification in the sense of Redtenbacher's nineteenth-century calls [3] reveals the untapped potential resulting from the thermal activation of combustion chambers. Accepting this challenge, the authors presented in [2] a mathematical and physical model of modifying the passive combustion chamber (BKS) into an active combustion chamber (AKS).
The principle of the active combustion chamber (AKS) operation, described in detail in [3, 4], assumes that the following thermodynamic cycles of engine operation are energetically increased by moving heat portions from previous cycles by subsequent transfer from the content (mixture) of the combustion chamber to the structure (metal) of the combustion chamber and then from the construction of the combustion chamber to the content of the combustion chamber. This two-way heat transfer is obviously due to the temperature difference. However, the method and time of this transfer is important.

„Portions of heat remain inside the combustion chamber but outside its contents. The result of this principle of operation of the active combustion chamber is that the excess heat stored in it for later use in the next phase of the engine's work cycle does not degrade fuel and the part of anergy stored for use (internal energy remaining in the chamber content after thermodynamic transformation) is not excreted together with exhaust gas. This process, called the heat portion buffering cycle, is parallel and concurrent with the engine's operating cycle. „ [4].

Heat transfer can take place via two paths: the upper one, located around GMP, marked as S1 and the lower one - S2.
The idea of an active combustion chamber in combination with other standard combustion chamber systems is presented in Figure 3.

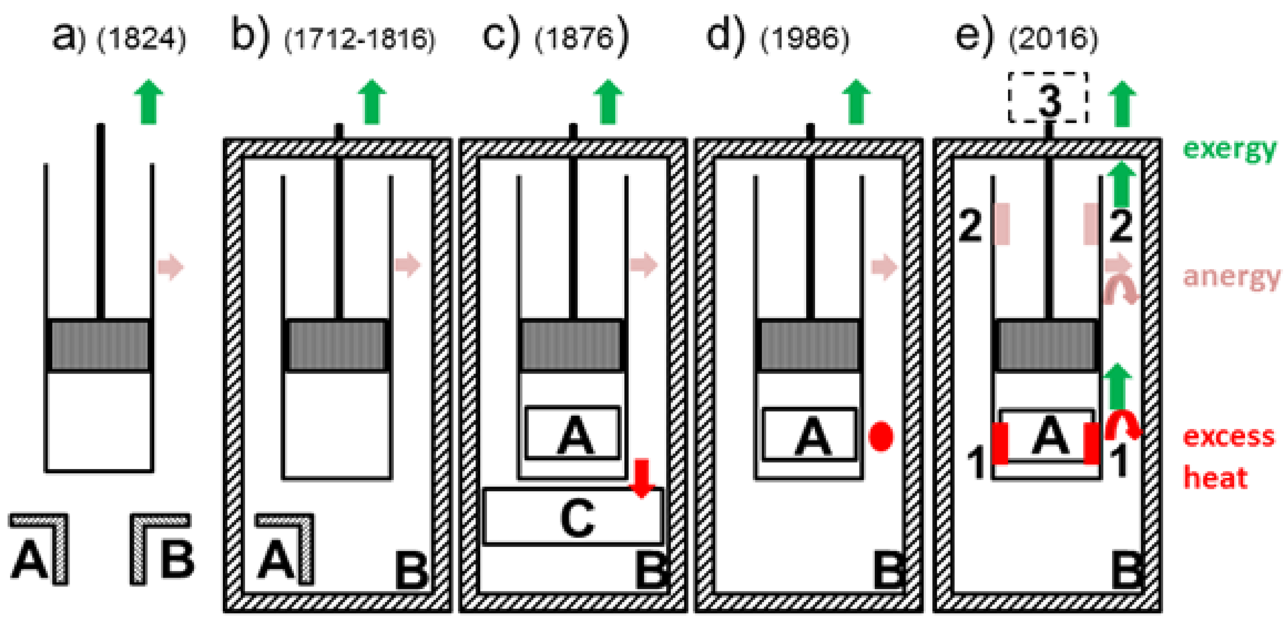

Fig. 3. Thermodynamic systems of piston chambers of heat engines

a) sketch of Carnot - hypothetical heat machine (1824) [5]
b) heat engine with external combustion, e.g. the first Newcomen steam engine (1712) or the Stirling engine (1816.)
c) heat engine with internal combustion, e.g. according to Reithmann (1873) and Otto (1876) with a passive combustion chamber (BKS),
d) thermally insulated passive chamber (BKS), e.g. tested by Woschni (1986),
e) authors' proposal to develop BKS into an active combustion chamber (AKS).

Designations: A - heat source, B - cold source (environment), C - cooler (external cooling),
1 - thermal buffers maintaining portions of excess heat, 2 - thermal buffers maintaining portions of anergy, 3 - receivers of exergy stream as mechanical energy,

Considering the passive combustion chamber (BKS), for example with a 510 J fuel charge, the balance of energy flow in the engine can be represented as in Fig. 4.

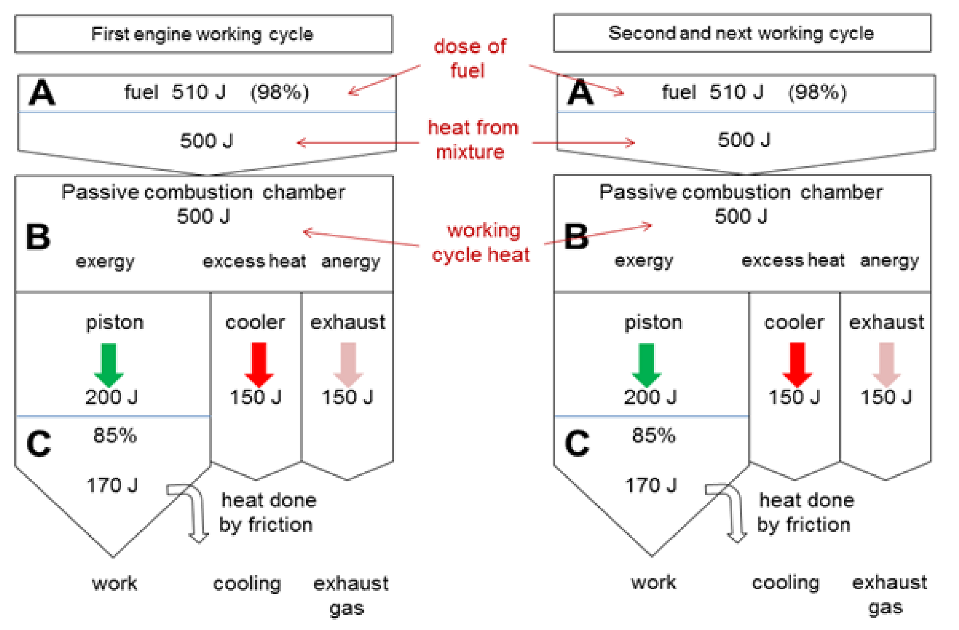

Fig. 4. Balance of energy flow from passive combustion chamber

The engine powered by 510 J of fuel dose loses some portion of energy (2%) already at the beginnin of the cycle as a result of thermal-flow processes giving 500 J to the chamber. In the passive (classic) combustion chamber this energy is dissipated into three main components, i.e. exergy - directed through the piston to the crank system, whose losses of approx. 15% are included in mechanical efficiency. 170 J remains to be used (for propulsion) which gives a useful efficiency of approx. 33%. The cooling system, transferring excess heat, absorbs 150 J - just like exhaust gas, which is an energetic expression of anergy. Implementing the second and next cycles, the balance is duplicated. A different process situation is when the active combustion chamber (AKS) is introduced - Fig. 5.
With the same initial assumptions for the first cycle as for BKS as a result of heat buffering, associated with active heat intake and dissipation (AKS), the fuel dose in the second and subsequent cycles can be reduced and the energy difference lies in the portions of energy transferred through the paths S1 and S2.
The first buffer path feeds the stream of energy transferred by the piston for use by the value of 50 J, which means that after taking into account the heat losses associated with friction phenomena, useful energy of 212.5 J is obtained. At the same time, excess heat and anergy are bound by the system exhaust gas and a cooling system that, if two buffering paths are in operation, gives a total (50 + 75) J of energy transferred to the next cycle. In this way, in the following ones, apart from the first cycle, a significant portion of heat feeding the combustion chamber is visible. In this way, a smaller dose of fuel with an energy of 382.6 J can be delivered to the combustion chamber, which together determines a useful efficiency of 42%.

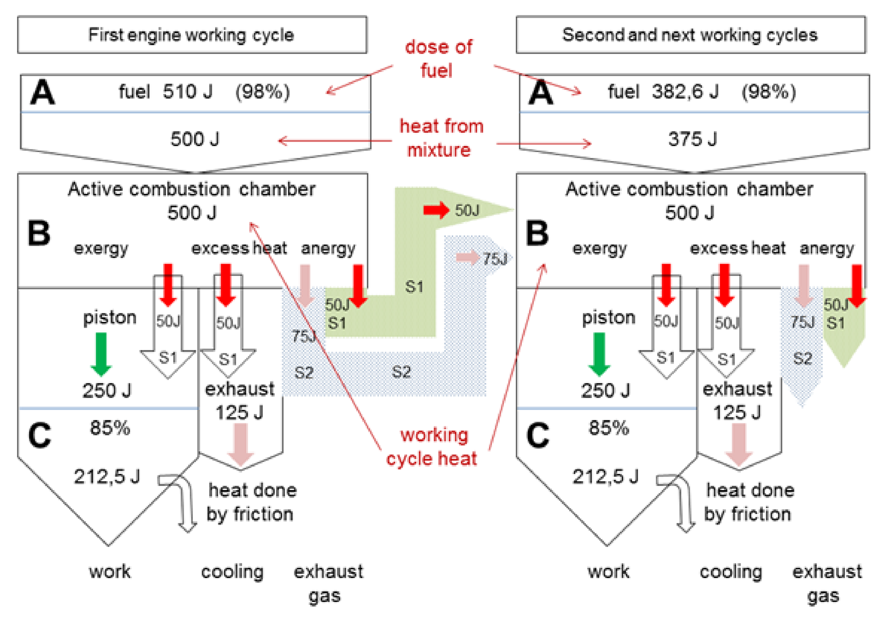

Fig. 5 Balance of energy flow from active combustion chamber

The two heat flow paths shown, S1 and S2, represent the potential of AKS solution and become the basis for consideration of reducing carbon dioxide emissions.
Solutions related to heat buffering in the combustion chamber refer to the active combustion chamber of the piston engine and the method of heat transfer in it, which are described in the international patent application of one of the co-authors of the article [4].

Research results and discussion

The paper includes example calculations related to the modification of the combustion chamber in a real BMW 2-liter twin-turbo four-cylinder diesel engine, installed, for example, on BMW 1-5 Series, Z4, X1-4 cars.
In theoretical considerations, two layers (S1 and S2) thermally separated from the engine structure were applied to the inner walls of combustion chamber limiting, among other things, chamber cooling.
The excess heat buffer - path S1 can be structurally selected for one operating point, the so-called base point. This can be for example the rated engine power or the engine speed corresponding to the selected vehicle speed. It means that, structurally, it is a buffer with constant thermal parameters and energy balances for other operating points depend on the physico-chemical properties of the basic point buffer. Consequently, the buffer parameters may deviate from the optimal values at the current operating point. However, according to the model, these deviations are small. This issue will be the subject of already initiated experimental identification.
The first layer S1 located at around Top Dead Center (TDC) is made of tungsten alloy and is planned to be deposited according to the model on the piston crown and cylinder head (also on valve crowns). It is also possible to deposit this layer on the inner cylinder surface. Second layer S2 placed at around Bottom Dead Center (BDC) on the cylinder surface is made of aluminum alloy.
Theoretical considerations were carried out in the following order:
- analysis of parameters of passive combustion chamber for the base point
- analysis of the development of a passive combustion chamber into an active combustion chamber,
- determination of the theoretical parameters of the proposed active combustion chamber.

The general model of changes in a single engine cycle adopted for the passive and active combustion chamber consists of the following functional blocks:
- introducing the charge at the set initial temperature as the new content of the combustion chamber and its compression,
- heating up the content of the combustion chamber by burning a mixture that contains a dose of fuel with a fixed portion of energy,
- moving energy without losses inside the combustion chamber thermally insulated from the surroundings,
- moving energy flows without losses, the source of which is the content of the combustion chamber and receivers are located outside the combustion chamber,
- a concurrent performance of useful work through the resultant force on the piston, i.e. providing rated power,
- removal of the content of combustion chamber with fixed internal energy that remained in it after transformations.

Knowing the technical and operational parameters of the tested internal combustion engine, results were obtained that determined the geometrical and thermodynamic quantities of active combustion chambers together with the prediction of carbon dioxide emissions - Tables 1 and 2.
The thermal structures of the combustion chambers are:
- thermally passive combustion chamber (BKS) as a subject to modification,
- an active combustion chamber (AKS) with buffer applied on path S1 for total buffering of excess heat,
- an active combustion chamber (AKS) with a buffer applied on the S1 path for total buffering of excess heat and a thermal buffer on the S2 path for the most effective buffering of anergy, consisting of portions from various heat sources, heating up the contents of the combustion chamber.

The external input parameter of the balance in each calculation profile is the dose of fuel introduced into the combustion chamber in a single operating cycle:
The first external output parameter of the balance in each calculation profile is a portion of exergy converted to useful work in a single stroke of the work in a single combustion chamber.
Since the principle of modification is to maintain mechanical performance parameters, the exergy output values should be equal.
The second external output parameter is the portion of anergy excreted in the exhaust gas.
Because the internal energy of the exhaust gas and resulting temperature are important in the operation of internal combustion engines, the calculation profile for the AKS chambers also gives the value of the change in the portion of excreted anergy in relation to the BKS chamber.

Table 1. Selected operational, geometric and thermodynamic parameters
of engine with active combustion chamber for the BMW 2-twin twin-turbo engine
at a rotational speed of 2000 rpm and for a vehicle speed of 100 km/h – the base point

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structure	parameter	unit	passive combustion chamber the base point	active combustion chamber	
				path S1	paths S1+S2
operating data	fuel consumption	$dm^3/100km$	5.76	4.40	2.54
	specific fuel consumption	g/kWh	205	157	90
	emission CO_2	g/km	152	116	67
	useful engine efficiency	%	41.22	53.99	93.68
	duration of the work stroke	ms	15.00	15.00	15.00
S1 thermal buffer on the piston crown	buffer area	cm^2	-	4.64	
	layer thickness	mm	-	0.09	-
	time for the heat wave to pass through the layer	ms	-	0.19	-
S1 thermal buffer on the inner surface of cylinder liner	buffer area	cm^2	-	9.27	-
	layer thickness	mm	-	0.09	-
	time for the heat wave to pass through the layer	ms	-	0.19	-
S2 thermal buffer on the inner surface of cylinder liner	buffer area	cm^2	-	-	31.06
	layer thickness	mm	-	-	0.13
	time for the heat wave to pass through the layer	ms	-	-	0.09
Parameters of single working cycle in single cylinder	fuel dose	mg	11.96	11.96	11.96
	output portion of useful work	J	210	210	210
	output portion of heat in the content of the combustion chamber at the beginning of the stroke	J	489	489	489
	portion of excess heat	J	127	127 balanced in the 2nd cycle	-
	portion of exergy turned into useful work	J	215	214 balanced in the 3th cycle	-
	portion of anergy after the stroke	J	147	158 averaged over n cycles	147 Completely absorbed portions of anergy

Table 2. Selected operational, geometric and thermodynamic parameters of engine with active combustion chamber for the BMW 2-twin twin-turbo engine at a rotational speed of 1600 rpm and for a vehicle speed of 60 km/h

structure	parameter	unit	passive combustion chamber the base point	active combustion chamber	
				path S1	paths S1+S2
operating data	fuel consumption	$dm^3/100km$	5.49	4.30	2.41
	specific fuel consumption	g/kWh	205	161	90
	emission CO_2	g/km	145	114	64
	useful engine efficiency	%	41.22	52.63	93.68
	duration of the work stroke	ms	18.75	18.75	18.75
S1 thermal buffer on the piston crown	buffer area	cm^2	-	4.64	
	layer thickness	mm	-	0.17	-
	time for the heat wave to pass through the layer	ms	-	0.19	-
S1 thermal buffer on the inner surface of cylinder liner	buffer area	cm^2	-	9.27	-
	layer thickness	mm	-	0.09	-
	time for the heat wave to pass through the layer	ms	-	0.19	-
S2 thermal buffer on the inner surface of cylinder liner	buffer area	cm^2	-	-	31.06
	layer thickness	mm	-	-	0.10
	time for the heat wave to pass through the layer	ms	-	-	0.05
Parameters of single working cycle in single cylinder	fuel dose	mg	8.54	8.54	8.54
	output portion of useful work	J	150	150	150
	output portion of heat in the content of the combustion chamber at the beginning of the stroke	J	349	349	349
	portion of excess heat	J	91	113 balanced in the 2nd cycle – by 24%	-
	portion of exergy turned into useful work	J	154	187 balanced in the 2nd cycle – by 21%	-
	portion of anergy after the stroke	J	105	119 averaged over n cycles	-105 Completely absorbed portions of anergy

In both considered cases, attention is focused on the extremely favorable balance of the combined buffer paths S1 and S2, which testifies to the potential of the active combustion chamber (AKS). It results from the parameters of the S2 buffer, which according to the theoretical model completely takes over a portion of anergy from exhaust gas.
Parameters determined as a result of the tests: total surface of the final temperature zone, as the surface of the S2 buffer mounted on the cylinder liner, the double time of passing through the piston of the final temperature zone, i.e. contact with the content of the combustion chamber are moderate parameters and undoubtedly require experimental identification that will allow the obtained very high values of useful efficiency and predictions of carbon dioxide concentration. On the other hand, the results obtained are concurrent with the considerations on adiabatic engines if there is no decomposition of the fuel as a result of the thermolysis process at high temperaturę. The results also coincide with the research in other centers [6, 7].
Transferring a portion of heat from the content of the combustion chamber to the buffer layer is completely analogous to collecting a portion of excess heat to the cylinder wall in the mode of cooling the content of the combustion chamber. When the initial temperature of the cylinder wall is not less than 420K, and the hypothetical initial temperature of the buffer surface after cooling with a new charge is about 350K, so the displaced portion of heat can be larger. At the same time, the total heat capacity of the buffer is at least three times higher than the absorbed portion of heat, so that the heat pulse does not reach the base of the buffer and the dynamics of heat portion displacement is appropriate to the engine operating conditions.
In addition to the use of excess heat, a further mathematically unequivocal increase in efficiency occurs by using a portion of anergy, although the basis of the second law of thermodynamics assumes the total excretion of anergy together with the exhaust gas. Considerations have shown, among other things, that for the AKS chamber with the first buffering path - S1 one should expect in the laboratory tests an increase of exhaust gas temperature and with a negative value of the change in the amount of anergy i.e. for AKS with two paths S1 and S2 the gas temperature will be lowered.
Without introducing accounting corrections, the authors leave this case for a wide discussion, while conducting laboratory tests on a real object, which is a single-cylinder, diesel engine.
Currently, tests at the Wrocław University of Science and Technology have been started with the implementation of the active combustion chamber solution. The thermal and ecological states of the passive combustion chamber were identified and work began on applying a buffer layer to the upper part of the cylinder liner and valves crowns - Fig. 6.

Fig. 6 Test stand with thermal and emission assessment of diesel engine and valve prepared for modification

Conclusions

The development of the active combustion chamber (AKS) project and the actual reduction of CO2 emissions in internal combustion engine to acceptable level can breakthrough the conflict between the necessary civilization mobility, environmental protection and preservation of current potential of the automotive industry.
The principle of AKS implementation in car concerns is a revolution without revolution - modification of engines while maintaining the existing production base and commonly used layer coating technologies.
The improvement in the use of fuel in AKS is based on the phenomenon of heating and cooling of solids, which is well known in nature and in technology.
An AKS solution is universal and can be used together with all known engine cycles as well as with other methods of improving engine operation and with all types of fuels used.
An AKS calculation is based on a precise balance of energy flows in the combustion chamber, which results from the law of energy conservation. Large reserves are maintained to allow possible corrections to the structure parameters

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