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Heat Characteristics and Emission Effect of a Fuel-operated Auxiliary Air Heater Fed with Fuel E10, E30 and E100

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Abstract

In order to increase the comfort of vehicle passengers in specific vehicle categories, the heating of the passenger compartment is not provided by the heat from the engine driving the vehicle but by an additional heating device. The study examines the effect of auxiliary heaters that use liquid fuels to heat the passenger compartment of vehicles. The device was operated during the test with two different mixtures containing bioethanol (E30, E100) and the original motor gasoline (E10). It aimed to understand the effects of different fuels, particularly heating performance, operating time and emissions. Based on the results, as the ethanol content increases, the temperature of the device's flame and heating air decreases. The experiments showed that in the case of E100 bioethanol, the average temperature measured in stable operating conditions was significantly lower than in the case of E10 motor gasoline. That suggests that an increase in the ethanol content reduces the heating performance. Another significant result of the study was that in the case of mixtures containing ethanol, a longer operating time is required to achieve the same amount of heat, which leads to additional fuel consumption. In addition, when using E100 bioethanol, the amount of harmful gases that are emitted increases significantly during the longer operating time. This observation can be important for evaluating the environmental impact and efficiency of vehicles.

Keywords

fuel operated air heater, heat quantity, emission, bioethanol

1 Introduction

Internal combustion engines that power vehicles generate heat and mechanical work as they operate. The chemically bound energy inherent in the used fuel is used [1]. The heat produced is called waste heat and is used indirectly to heat the passenger compartment under a given temperature. However, there are situations in vehicles where the heat is needed, but the engine is not supposed to be started only for heat production. There are economic reasons for this. Such operational situations can be, for example, (i) heating the passenger compartment in winter before starting the engine, (ii) heating the passenger compartment at night for sleeping in winter, or preheating the engine in order to reduce the time of the warm-up phase. With this, the possibility of improving engine operating parameters, e.g. wear or fuel consumption and emissions [2]. Auxiliary heating devices can be classified into two groups according to where the source of heating energy comes from. The source can be electrical energy or energy chemically bound in liquid fuel. Today, devices of various designs and performance levels are on the market from both of the above types [3–6]. Devices that use liquid fuel may use the original fuel of the vehicle's engine, or there are devices designed to run on renewable fuel [7]. Operation with renewable fuel affects the amount of heat delivered and the amount of pollutants emitted by the device [8, 9]. The devices can be further divided into two groups, according to the aspect that they heat the air, which can be used to heat the passenger compartment, or they heat the coolant of the internal combustion engine, which can be effective for the engine in terms of the above parameters [3–6].

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Our current work examines the thermal properties of a device operating with liquid fuel. The original fuel of the tested device is gasoline, but for experimental purposes, the device is operated with mixtures of different proportions of gasoline and bioethanol. We are also looking for the difference in the quantity of heat released with different fuels and to what extent this causes changes in emissions.

2 Materials and methods

Three different fuels were used to test the auxiliary heater. The first was the commercially available E10 fuel, the properties of which can be found in the relevant European standard [10]. The second fuel tested was a blend (E30) mixed from base fuel and E100 fuel on a volume basis, so it contains 30 V/V% ethanol and 70 V/V% motor gasoline. The third tested fuel was not a mixture but an E100 fuel. We obtained this from a Hungarian production plant, and according to its product sheet, it meets the requirements of the European standard for bioethanol [11]. The properties of the two standard fuels considered the most important in terms of heat production are summarized in Table 1 [10, 12].

Based on the data in the Table 1, the density of the two materials hardly differs. That also means that volumetric transport delivers a fuel mass similar to the combustion chamber. The calorific value of ethanol is approximately 65% of the calorific value of motor gasoline, which can significantly affect the amount of heat generated from combustion. The difference in the heat of vaporization values is also significant since the heat of vaporization of gasoline is almost half of the heat of vaporization of ethanol. This results in worse mixture formation, resulting in lower heat release and higher pollutant emissions. The last parameter is the theoretical air requirement, which is significantly lower in the case of ethanol than in the case of motor gasoline. That means that by adding the same amount of combustion air to a unit mass of fuel, ethanol operates with a significantly leaner mixture than gasoline operation, which also points toward lower heat release.

The heater, equipped with all necessary sensors and accessories, was meticulously mounted on a frame and placed in a state-of-the-art engine brake room. To ensure the repeatability of our measurements, the temperature and humidity of the room (set at a controlled 15 °C and 30 relative humidity %) were carefully regulated in the air supply system. That allowed us to isolate the heat characteristics influenced solely by the fuels. All measurements were initiated from this ambient temperature, and the parameters of the air inhaled by the device mirrored these conditions during operation. After each fuel operation, the device was allowed to temper until it returned to its initial conditions, ensuring consistent and reliable results.

Table 1 Important properties of fuels in terms of heat production [10, 12]

Fuel → Parameter ↓	E10	Ethanol (C_2H_5OH)
Density at 15 °C [kg/m^3]	720.0÷775.0	789
Lower heating value [MJ/kg]	43.9	28.6
Heat of vaporisation [kJ/kg]	419	904
Theoretical air demand [kg_{air}/kg_{fuel}]	14.7	9.0

The test duration was set at a practical 30 minutes, a time frame that, according to surveys [3], mirrors the average duration required to heat a passenger compartment on a cold winter morning. The manufacturer offers three distinct operation modes for the device: Eco, Normal, and Boost modes [3]. For our measurements, we opted for the Normal mode, which aligns with real-world usage scenarios and enhances the practicality of our findings.

The heat output was determined using Eq. (1) [13]:

$$P = c_{air} \cdot \dot{m} \cdot \left(t_{heating} - t_{inlet}\right), \tag{1}$$

where: c_{air} is the heat capacity of the air at 15 °C [kJ/kg K], m point is the mass flow of the incoming air [kg/s], $t_{heating}$ is the temperature of the air that can be used for heating the passenger compartment [K], t_{inlet} is the air temperature, which enters the device [K]. The amount of heat released is the product of heat output and time [13].

3 The experimental setup

Fig. 1 shows the heater, the related units, the units required for its operation, and the retrofitted sensors. The device's characteristics are listed in Table 2, and the elements of the entire measuring system are listed in Table 3.

The most important parameters for evaluating the thermal characteristics were (i) Room temperature and humidity, (ii) mass flow of the inhaled air, (iii) flame temperature, (iv) heating air temperature and (v) fuel consumption

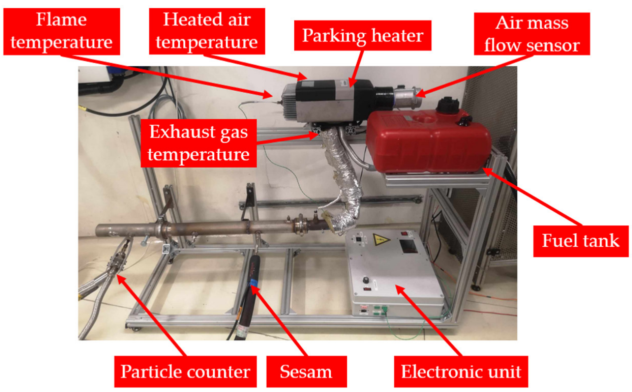

Fig. 1 The experimental setup [own editing]

Table 2 Technical parameters of the investigated heater [own editing]

Nominal heat power	5.5 kW (Boost) 5 kW (Normal)
Type	Cabin (air) heater
Fuel feeding	diaphragm pump
Atomisation	metal mesh
Vaporisation	glow plug
Fuel	Gasoline (E10)

Table 3 Parts of measurement system [own editing]

Path	Parameter	Instrument, device	Make, type
Air	Intake air humidity and temperature	Humidity and temperature sensor	Vaisala HMT310
	Heating air temperature	Temperature sensor	Webasto
	Intake air mass flow	Air mass flow meter	Hitachi 059906461D
Combustion	Flame temperature	Thermo couple	N type sensor with QuantumX MX1609B
Exhaust	Exhaust temperature	Thermo couple	K type sensor with QuantumX MX1609KB

(a based on fuel pump frequency). The Fig. 1 also shows sensors, e.g. lambda sensor and sampling points required for emissions analysis, which were also part of the entire measuring system.

However, the results of this study are only referred to in the Section 4. The signals of the sensors were implemented in the signal management system of engine test bench [14], and the evaluation of the signals was carried out using the evaluation program of the engine test bench [15].

4 Results and discussion

4.1 General description of the generation of heating air

The heater circulates the air of the space and cabin to be heated as shown in Fig. 2 [16].

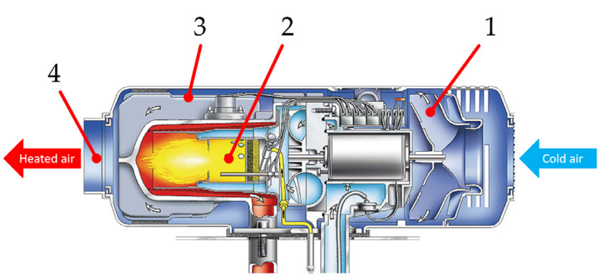

Fig. 2 The process of generating heating air [16]

The process can be described as follows:

- The air of the heated space enters the heater's housing due to the suction effect created by the radial fan marked with number 1. The heater and the plastic casing surrounding it are designed so that the air to be heated flows around the device body towards the combustion chamber.
- During fuel burning, the flame (2) created in the combustion chamber and the exhaust gas leaving the combustion chamber heat up the aluminium heating element of the device marked with number 3.
- To increase the heat-dissipating surface, the heater was equipped with ribs in the longitudinal direction. The air flowing between the heated ribs heats up.
- The already heated heating air leaves the device at point 4.

4.2 The effect of increasing the bioethanol content on the heating performance

We used the same operating program (Normal mode) [3] during the tests, so the device settings did not change. It means that the fan motor's speed and the fuel pump's frequency were run according to Normal mode for all measurements. The function of the two operating parameters were recorded by us and plotted in Fig. 3.

The original program of the devices and the various sensors placed in them cannot distinguish fuels, so whatever fuel fuels the combustion, the devices always follow the same factory operating program.

In Fig. 4, it can be observed that as the ethanol content increases by volume (E10 → E100), the flame's temperature and the heating air in the device decreases significantly. With a 10% bioethanol content, the average temperature during stable operation is approximately 966 °C. In comparison, this value is 911 °C with a 30% renewable fuel fraction (E30) and only 787 °C during pure ethanol

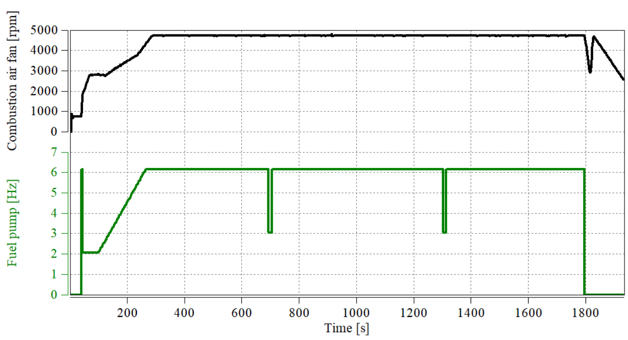

Fig. 3 Speed of the fan and frequency of the fuel pump during the test period in normal mode

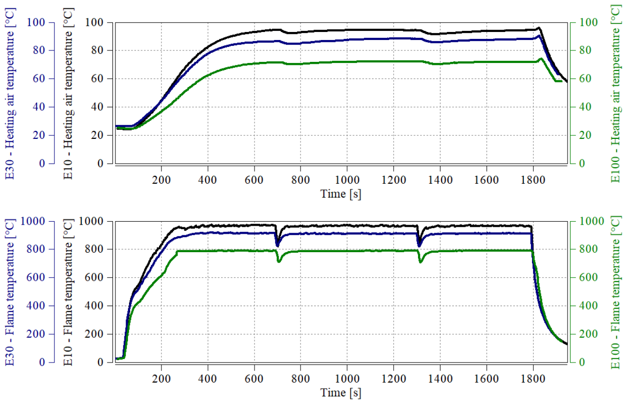

Fig. 4 Changes in temperature of flame and heating air along the investigated fuels

combustion, which is the currently commercial compared to the E10 fuel available on the market, the E30 fuel shows a −5.7% decrease, and the E100 −18.5% decrease.

A similar decrease can be seen in the temperature of the heating air blown out by the stationary heating device. In the case of E10 fuel, under stable operating conditions, the average temperature of the exiting heating air is 94 °C; for E30, it is 87 °C; and for E100, it is 72 °C. Compared to the base fuel, the temperature of the heating air decreases by −7.5% during the combustion of E30 fuel and by −23.5% during the combustion of pure bioethanol, with the same amount of fuel consumption.

The authors do not know how to determine offcially the factory performance of the devices. The nominal heating power of the device we use is 5.5 kW. The device can transmit this for a shorter time in Boost mode. In normal mode, the manufacturer specified a power of 5 kW when using commercially available fuel. The heating performance was determined by calculation with the three fuels we examined, and the results are plotted in Fig. 5 as a function of time.

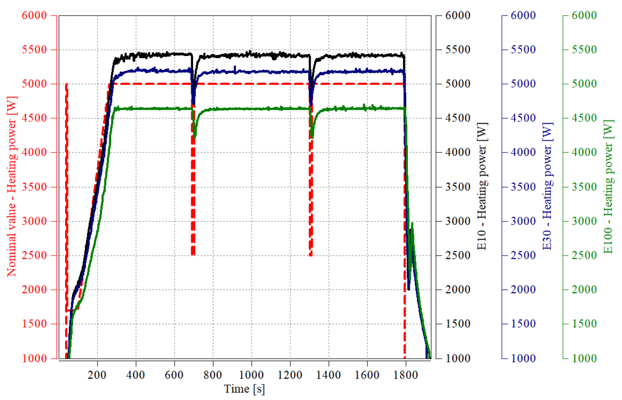

Fig. 5 Theoretical and calculated heat power over the time for the three different fuel

A significant temperature decrease was observed during the measurement of the flame's temperature and the heating air as the bioethanol content increased. As a result, we could already assume in advance that we can experience a similar trend in the change of heating power. During the theoretical calculations, when using E10 fuel in a stable operating state, the average output was 5418 W, which is 8.4% higher than the 5000 W output specified by the manufacturer. With an E30 mixture, the average power is 5176 W, which shows a −4.5% decrease compared to E10. With the combustion of E100 pure bioethanol, the average heating power in stable operating conditions is 4638 W, which is a decrease of −4.4%. The measured values are summarized in Table 4.

4.3 Excess fuel consumption and pollutant emissions caused by the reduction in heat performance

Table 5 summarizes the total amount of heat emitted by burning the tested fuels, including the 1800-second test cycle we chose and the automatic cooling cycle after stopping the device's heating cycle.

In order to obtain the same amount of emitted heat by burning an E30 mixture and E100 bioethanol, as in the case of E10, the device needs to be operated for a longer time. Fig. 6 shows how the operating time changes as the bio content of the fuel increases.

Using E10 fuel, the heat generated for 1800 seconds and during the subsequent 156-second automatic cooling period is 9.2 MJ. Using the E30 mixture with lower heating power, the device must be operated for 77 seconds longer during the heating cycle to obtain the heat obtained by

Table 4 Summary of the heating characteristics for E10, E30 and E100

Fuel →	E10	E30		E100	
Parameters ↓			Changes compared to E10		Changes compared to E10
Flame temperature	966 °C	911 °C	−5.7 %	787 °C	−18.5%
Temperature of heating air	94 °C	87 °C	−7.5%	72 °C	−23.5%
Heat power	5418 W	5176 W	−4.5%	4638 W	−14.4%

Table 5 Heat quantities generated during the running and the cooling down processes

Fuel →	E10	E30		E100	
Parameter ↓			Change compared to E10		Change compared to E10
Heat quantity	9.2 MJ	8.8 MJ	−4.4 %	7.9 MJ	−14.2 %

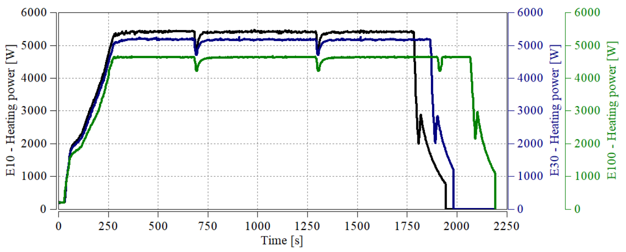

Fig. 6 Change in the duration of the operating cycle during the use of increasing bioethanol content in order to achieve the same amount of generated heat

burning the E10 fuel. For E100, this time value increases to 277 seconds. That means that the device is not stopped at 1800 seconds but continues to operate in a stable state. During the extra operating time, it is necessary to burn 0.011718 kg of E30 mixture and 0.041765 kg of E100 fuel. During the increased operating time, the amount of solid and gas-phase harmful substances increases by burning the excess fuel, as summarized in Table 6. The primary data of the table, the fundamental emission values, come from the authors' previous publications [17, 18].

No significant increase in the number of emitted solid particles can be seen with a longer operating time. In the case of an E30 fuel mixture, the increase is +0.1%, while E100's value is +1%. For the primary gaseous pollutants such as NO_x, CO, CO_2, N_2O, and E30, each gas showed an increase of less than 5% with an additional heating time of 77 seconds. A significant increase in NOx, CO2, and N2O gases during the 277-second longer run was observed when burning E100, which is approximately +15%. THC and CH_4 gases are produced during the device's start-up and burn-out operation phases, so additional operation in stable operating conditions does not result in additional emissions.

Table 6 In order to emit the same amount of heat as E10 fuel, additional pollutant emissions caused by longer driving with E30 and E100 fuels

Fuel → Exhaust components ↓	E10		
PN [#]	956 417 051		
NO_x [g]	0.89		
CO [g]	0.41		
CO_2 [g]	945		
THC [g]	0.532		
CH_4 [g]	0.0022		
N_2O [g]	0.0075		
Fuel →	E30		
Exhaust components ↓	original value	new value	increase
PN [#]	483 136 882	483 632 356	+495 474 [0.1%]
NO_x [g]	0.66	0.69	+4.3%
CO [g]	0.33	0.34	+2.9%
CO_2 [g]	864	904	+4.4%
THC [g]	0.329	0.329	+0.0%
CH_4 [g]	0.0018	0.0018	+0.0%
N_2O [g]	0.0084	0.0087	+3.4 %
Fuel →	E100		
Exhaust components ↓	original value	new value	increase
PN [#]	165 139 854	166 838 975	+699 121 [1%]
NO_x [g]	0.27	0.32	+15.6%
CO [g]	0.34	0.36	+5.6%
CO_2 [g]	674	787	+14.4%
THC [g]	0.019	0.019	+0.0%
CH_4 [g]	0.0013	0.0013	+0.0%
N_2O [g]	0.0111	0.0129	+14.0%

5 Conclusion

Tests were meticulously conducted on a stationary heating device, operating with a base fuel (E10), another gasoline-ethanol mixture (E30) and pure ethanol (E100). A comprehensive comparative analysis revealed the profound impact of bioethanol content on the device's heating performance and pollutant emissions. Our results underscore the following pivotal conclusions:

- The alteration in fuel composition was found to have a substantial influence on the operating parameters and performance of the heating equipment. As the ethanol content escalates, the temperature of the flame and the blown heating air diminishes, directly correlating with the decrease in the device's performance. These findings were derived from meticulously conducted tests, ensuring the validity and reliability of our results.
- When using E10, E30 and pure bioethanol fuels, it can be observed that the heating performance of the device decreases. Based on theoretical calculations, in the case of E30 and E100 fuels, we can experience a significant reduction in performance compared to E10.
- The increase in bio content of the fuel necessitates more extended operation of the device to achieve the same heat output, leading to escalated excess fuel consumption and emissions. This finding has

significant practical implications, highlighting the need to consider fuel composition in heating device operation carefully.

- During the examination of harmful emissions, it can be observed that the additional fuel consumption associated with longer operating hours increases the emission of gaseous pollutants such as NO_x, CO, CO_2 and N_2O, especially in the case of E100 fuel.
- However, there is no significant increase in particulate matter due to longer operating time, and certain gaseous pollutants such as THC and CH_4 do not show an increase with additional operating time at a steady state.

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