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Experimental study of the low-melting hydrocarbons regression rate in the air flow

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Abstract. Gasification of organic and inorganic materials in a high-temperature gas flow is a promising technology for various industrial applications like chemical industry, waste processing, rocket and air-breathing propulsion, etc. However, the characteristics of the gasification process of low-melting hydrocarbon materials remain insufficiently studied so far. In this work, experiments on the gasification of cylindrical polypropylene (PP) samples by the airflow passing through multiple longitudinal channels 3 to 4 mm in diameter and 200 mm long are performed. The temperature, pressure, and velocity of the airflow in the experiments range from 300 to 1500 K, 0.35 to 1.38 MPa, and 17 to 100 m/s. As expected, oxygen available in the airflow interacts with PP and creates an additional heat source for PP gasification, thus, enhancing the gasification process. At an airflow temperature of 1480 K, the maximum mass flow rate of gasification products is shown to attain 17.7 g/s. The minimum ratio of the mass flow rates of the airflow and gasification products reaches the value of 2. In tests with airflow temperature of 300 K, the maximum mass flow rate of gasification products is 8.5 g/s. The minimum ratio of the mass flow rates of airflow and gasification products is 5 in these experiments.

1. Introduction

The concept of solid-fuel ramjets is currently associated mainly with the scheme of a ducted ramjet engine or a Throttleable Ducted Rocket (TDR) [1-2]. A mandatory element of the TDR is a gas generator (GG) aimed to gasify a solid fuel with a minimum amount (10–20%) of an oxidizer. Such an amount of oxidizer allows gasification of solid fuel due to its partial combustion in the GG and feeding the resulting gaseous products to the main ramjet combustion chamber, where they are completely burned in a high-speed flow of atmospheric air.

In the recent scientific literature, another relevant direction is discussed actively, that is the development of a low-temperature GG for gasification of low-melting fuels (LMF) like polymers (polyethylene, polypropylene (PP), polystyrene, polybutadiene, etc.) with a melting point of about 100 °C [3-7]. In the cited references, the design of a two-chamber GG with a sequential arrangement of a conventional solid propellant and LMF is studied numerically. In this design, burning of solid propellant generates a flow of high-temperature combustion products, which passes through the porous layer of LMF and gasifies it. In contrast to LMF gasification by a flow of combustion products, the use of air as a carrier gas could be considered more beneficial due to the possibility of obtaining an additional heat source for LMF gasification by partial burning of the LMF material.



The objective of this work is to study experimentally the gasification of PP in airflow. The main issues addressed are the ways of arranging PP combustion in airflow and the influence of the airflow temperature and mass flow rate on the yield of gasification products. These objective and issues are the novel distinctive features of this research.

2. Description of the experimental setup

Figure 1 shows the design of the experimental laboratory-scale GG. At the left end of the GG there is combustion chamber 3 and spark plug 13 of the fire heater operating on combustion of the stoichiometric hydrogen–oxygen mixture. In mixing chamber 5, the carrier gas (atmospheric air) is heated to the required temperature due to mixing with the combustion products. Thereafter, the heated carrier gas is fed through leveling pre-chamber 6 and profiled nozzle 7 to LMF test sample 8. Polypropylene of the PP H030 GP/1 brand is used as an LMF. After passing through the LMF test sample, the resultant gas flow enters small cylindrical channel 9, which ends with throttling insert 10 with orifice diameter of 6.5 mm. The use of a throttling insert allows maintaining the subsonic flow velocity in the GG. The exhaust gases expel from the GG to a vacuum tank (not shown in figure 1).

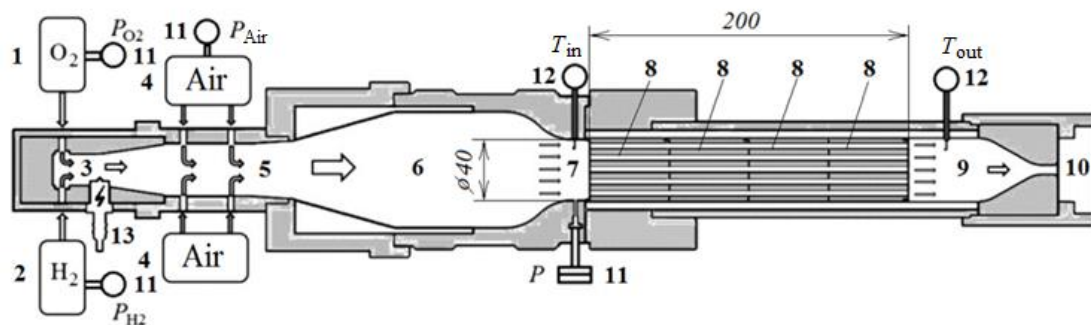


Figure 1. Scheme of laboratory experimental GG.

Two series of experiments are performed with the GG. The results of these series are presented below.

3. The results of the first series of experiments

In the first series of experiments, the airflow entering the GG is heated by combustion of hydrogen–oxygen mixture in a fire heater. The PP test sample is assembled from 4 cylindrical elements with diameter of 40 mm and length of 50 mm (figure 2). Each element has 19 evenly spaced longitudinal channels 3 mm in diameter. The total length of the test sample is 200 mm.

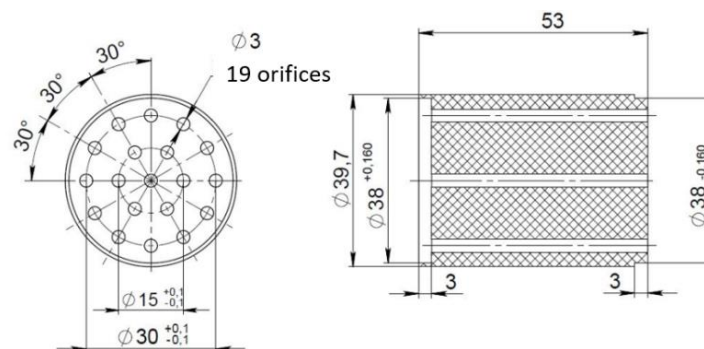


Figure 2. Test samples PP in the first series of experiments.

The experimental procedure is as follows. The command of a synchronization system triggers the data acquisition system and opens the valves of oxygen and air supply. In 200 ms, it triggers the spark plug and opens the valve of hydrogen supply. The mass flow of hydrogen in the experiments ranges from 0.2 g/s to 0.7 g/s, depending on the desired temperature of the carrier gas. In 300 ms, the spark plug is turned off, implying that the hydrogen–oxygen mixture is ignited, and its combustion is established. The airflow entering the GG is then heated to a preset temperature and directed to the channels in the LMF test sample to heat and gasify the sample material. The mass flow rates of hydrogen and oxygen are chosen so that the mass fraction of oxygen in the carrier gas entering the LMF test sample and consisting of steam, oxygen, and nitrogen is close to 23%, the same as in pure air. Within the LMF test sample, chemical reactions between oxygen present in the heated carrier gas and PP gasification products lead to generation of additional heat for PP gasification. The operation of the GG is terminated in 2300 ms when the synchronization system closes the valves of hydrogen, oxygen, and air supply. The data acquisition system is turned off in 3000 ms.

Table 1 shows the measured mass flow rates of hydrogen (G_{H_2}), oxygen (G_{O_2}), and air (G_{Air}) supplied to the GG in some representative experiments. Also presented are the total mass flow rate of the carrier gas (G_{in}), the mass flow rate of oxygen ($G_{O_2,in}$), and the mass fraction of oxygen ($Y_{O_2,in}$) at the inlet of the test sample. In all the experiments, the total mass flow rate of the carrier gas entering the PP test sample (G_{in}) is seen to remain constant at a level of 35–36 g/s, and the mass fraction of oxygen in the carrier gas is ~23%.

Table 1. Results of Experiments on PP Gasification by Heated Air.

No.	Test No	G_{H_2} , g/s	G_{O_2} , g/s	G_{Air} , g/s	G_{in} , g/s	$G_{O_2,in}$, g/s	$Y_{O_2,in}$, %
1	34	0.29	3.02	32.79	36.10	8.24	22.83
2	32	0.36	3.74	31.51	35.60	8.15	22.88
3	30	0.42	4.61	30.37	35.40	8.24	23.26
4	23	0.53	5.50	29.07	35.10	7.95	22.64
5	25	0.60	6.45	28.65	35.70	8.24	23.08
6	27	0.71	7.57	27.92	36.20	8.31	22.96

Table 2 shows the time-averaged (over time $t_g \approx 1.0$ – 1.8 s) characteristics of the gasification process. Increasing of the carrier gas temperature T_{in} from 900 to 1480 K is seen to increase the yield of PP gasification products (G_{PP}) from 4.7 to 17.7 g/s, whereas the ratio of the mass flow rate of the carrier gas to that of PP gasification products (G_{in}/G_{PP}) decreases from 2.9 to 1.8.

Table 2. Time-averaged characteristics of PP gasification by heated air.

No.	Test No.	t_g , sec	T_{in} , K	T_{out} , K	P_{in} , kPa	G_{PP} , g/s	G_{in}/G_{PP}
1	34	1.065	880	729	723	4.7	7.7
2	32	1.512	1015	1008	1075	12.4	2.9
3	30	1.698	1106	1100	1204	14.6	2.4
4	23	1.814	1272	1054	1196	15.2	2.3
5	25	1.836	1348	1119	1295	16.4	2.2
6	27	1.842	1483	1091	1380	17.7	2.1

Figure 3 shows typical records of pressure (P_{in}) in the GG and temperatures upstream (T_{in}) and downstream (T_{out}) of the LMF test sample in experiments with PP gasification by hot steam-air mixture.

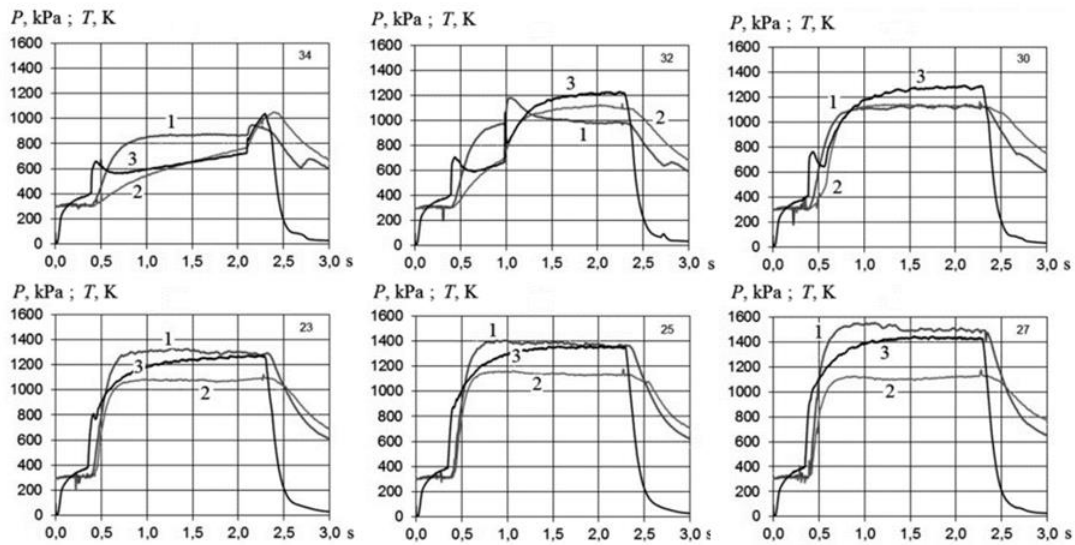


Figure 3. Typical records of temperature and pressure during PP gasification by heated air.
1 - T_{in} , 2 - T_{out} , 3 - P_{in} .

4. The results of the second series of experiments

In the second series of experiments, unheated air (at room temperature) is used as the carrier gas. Unlike the first series, PP test samples are assembled from 10 cylindrical elements with diameter of 40 mm and length of 20 mm (figure 4). Each element has 19 evenly spaced longitudinal channels 4 mm in diameter. All other details of the experimental setup are the same as in the first series of tests.

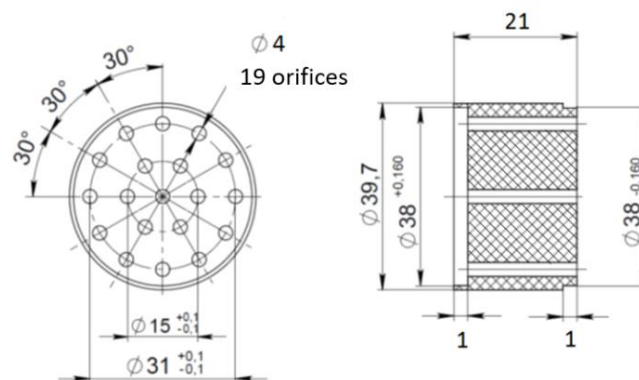


Figure 4. Test samples PP in the second series of experiments.

The experimental procedure is as follows. The command of the synchronization system turns on the data acquisition system and opens the oxygen and air supply valves. In 200 ms, the system starts triggering the spark plug and in 300 ms it opens the hydrogen valve to start combustion in the fire heater. After 300 ms of operation, the spark plug is turned off while oxygen and hydrogen supply to the GG is continued to support combustion. After 800 ms of operation (ignition stage), the oxygen and hydrogen valves are closed and only the air of room temperature is supplied to the GG with the already preheated PP test sample. Special experiments indicate that the average mass loss of the PP test sample at the ignition stage is 6.8 g. Thereafter, due to the interaction of oxygen available in the airflow with the preheated walls of the PP test sample, the combustion of PP in the sample channels is established, which provides heat for gasification of the sample material. The exhaust gas expelling

from the GG through the throttling insert is mainly composed of the PP combustion and gasification products, nitrogen and residual oxygen. The operation of GG is terminated in 5300 ms by closing the valve of air supply.

Figure 5 shows typical pressure and temperature records in the experiments of the second series. As seen, immediately after the termination of the ignition stage, the temperature of the carrier gas at the inlet of the PP test sample decreases to 300 K, while the outlet temperature remains at the level of 1000–1100 K. This is the indication of the self-sustained combustion process in the test sample.

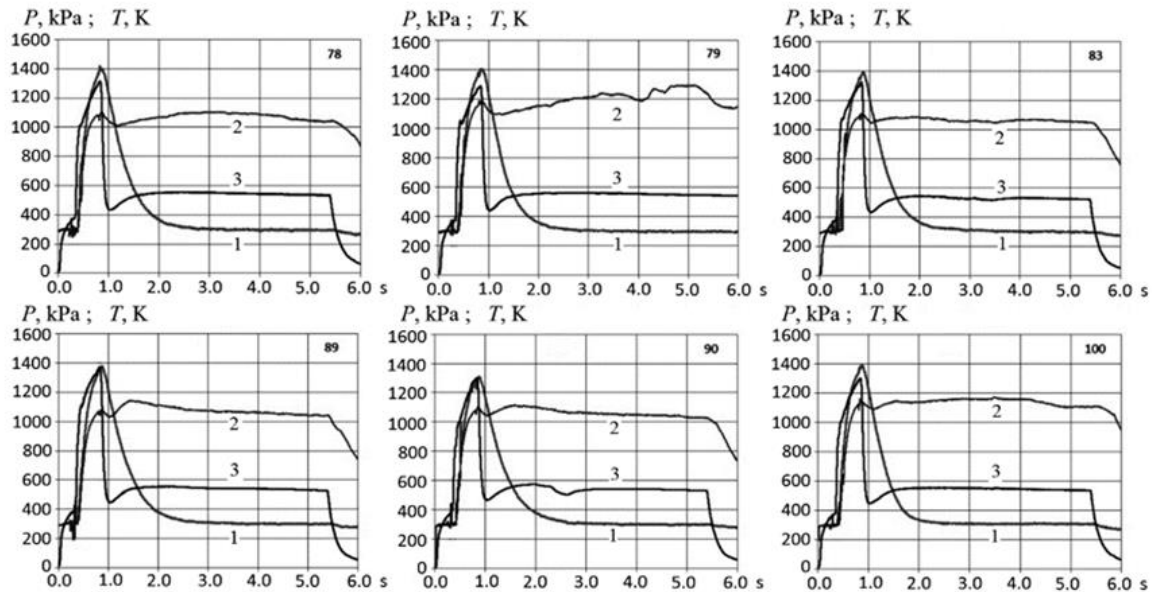


Figure 5. Typical temperature and pressure records during PP gasification by unheated air.
1 - T_{in} , 2 - T_{out} , 3 - P_{in}

Table 3. Time-averaged test results of PP gasification with cold air.

No.	Test No.	G_{Air} , g/s	T_{in} , K	T_{out} , K	P_{in} , kPa	Δm , g	G_{PP} , g/s	G_{in}/G_{PP}
1	78	27.5	304	1 080	546	21.33	4.68	5.88
2	79	27.5	300	1 189	538	34.75	4.06	6.78
3	83	27.5	310	1 061	529	20.53	4.50	6.11
4	89	27.5	310	1 065	539	22.47	4.93	5.58
5	90	27.5	307	1 055	535	23.52	5.16	5.33
6	100	27.5	310	1 142	546	18.41	4.04	6.81
7	103	27.5	305	1 085	523	16.79	3.68	7.47
8	105	33.0	333	1 066	691	28.77	6.31	5.23
9	107	27.5	304	1 031	545	24.41	5.35	5.14
10	108	33.0	307	1 107	695	29.45	6.46	5.11
11	109	42.0	298	1 227	903	32.75	7.18	5.85
12	110	42.0	297	1 200	887	38.71	8.49	4.95

Table 3 shows the time-averaged (over $t_g \approx 2.0$ – 5.3 s) characteristics of the gasification process. The yield of PP gasification products (G_{PP}) is seen to attain 4–5 g/s, whereas the ratio of the mass flow rate of the carrier gas to that of PP gasification products (G_{in}/G_{PP}) ranges from 5 to 7.

5. Conclusion

The laboratory-scale gas generator aimed at gasification of a low-melting combustible (polypropylene) in a carrier gas is designed, fabricated, and tested. Two series of experiments on gasification of polypropylene samples in a carrier gas with different temperatures are performed. In the first series, the carrier gas is represented by the airflow continuously (during the entire test fire) heated by combustion of the fuel-lean hydrogen–oxygen mixture. Chemical reactions between oxygen available in the heated carrier gas and the gasification products provide additional heat for polypropylene gasification. In the second series, the carrier gas is represented by a pure airflow. Initially, the airflow is heated by combustion of fuel-lean hydrogen–oxygen mixture to ignite a polypropylene sample. After ignition, the supply of hydrogen and oxygen is terminated, and the polypropylene sample is gasified solely due to the heat generated by continuous combustion of the gasification products in the airflow. In both series, the polypropylene samples are assembled from several (4 to 10) cylindrical elements with multiple (19) longitudinal channels 3 or 4 mm in diameter. The main issue addressed in this study is the effect of the carrier gas mass flow rate and temperature on the overall yield of polypropylene gasification products.

In the experiments of the first series, the air temperature, pressure, and velocity of the carrier gas are ranged from 700 to 1500 K, 0.57 to 1.38 MPa, and 60 to 100 m/s, respectively. The maximum mass flow rate of gasification products is 17.7 g/s. The minimum ratio of mass flow rates of air and gasification products is 2.

In the experiments of the second series, the airflow temperature is fixed at 300 K, whereas pressure and velocity of the airflow are ranged from 0.35 to 1.0 MPa and from 17 to 19 m/s, respectively. The maximum mass flow rate of gasification products is 8.5 g/s. The minimum ratio of mass flow rates of air and gasification products is 5.

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