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Experimental Study on the Effect of Water Injection on a Micro Turbojet Engine[1]

Due to increasing emissions in the 21st century, aviation industry faces a rising pressure to reduce its contribution to air pollution. A possible way to mitigate such harmful effects on the environment is to use water injection as a thrust augmentation method which was developed in the 1960s. Since the emergence of modern engines, the need for the performance-enhancing effect of water injection has become abandoned. However, considering its beneficial impact on both emissions and engine structure, it can still be used as an alternative nowadays as well. As a result of the cooling effect of water injection, the service life of engine components extends which could also lead to a reduction in maintenance and operating costs. This paper presents how water injection on TKT-1 experimental jet engine affects performance and emissions. The modifications implemented on the test bench enabled us to obtain a measure of the water injection operation with the nozzle placed in the intake duct. Results reveal that such method has no visible impact on the increase of thrust due to the experimental environmental conditions and the limitations of the system. Nevertheless, water injection proved to be effective in reducing emissions. In addition to the beneficial effect of lower gas temperature throughout the turbine section of the engine, the emissions of NOx gases also fall significantly (i.e. 30%) compared to dry operation.

Keywords: *emissions, thrust augmentation, water injection, micro gas turbine, jet engine*

1. Introduction

Water injection in the past was used on low bypass engines mostly to augment thrust, which proved to be successful. In hot weather conditions, jet engines could not produce as much thrust as it would have been needed at takeoff, so the only option to reach the required power was water injection at that time. Water injection was generally used during takeoff between 0 and 3,000 feet. These systems were used on the early 747s with the JT9D-7AW engines [1]. Even Honeywell [2] and Rolls-Royce [3] used this construction on their engines. Although at the time the only goal was to increase thrust, water injection also significantly reduces emissions. The primary source of NO2 and NO is burning fuel at high temperatures.

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These are collectively called thermal NOx. These environmentally harmful substances are formed at temperatures above 1,300°C, which is often exceeded in the combustion chamber and the turbine section of the engine [4].

Due to this emission-reducing effect, water injection could be used even nowadays in the aviation industry to mitigate the emissions. Furthermore, this kind of emission reduction does not only mean less pollution but also cost savings for the airlines because of the environmental fees, which must be paid after the amount of pollution caused by the engines [5]. Recent studies revealed that water injection can provide up to a 30% increase in thrust while the NOx emissions are reduced by 47% [6].

Another benefit of this method is the flame temperature cooling effect, which helps to extend the hot section service life by reducing the thermal load.

In terms of cost, this means savings for the airline as it requires less turbine maintenance. Figure 1 shows how investing in water injection affects maintenance cost savings in case of an airliner [7], [8].

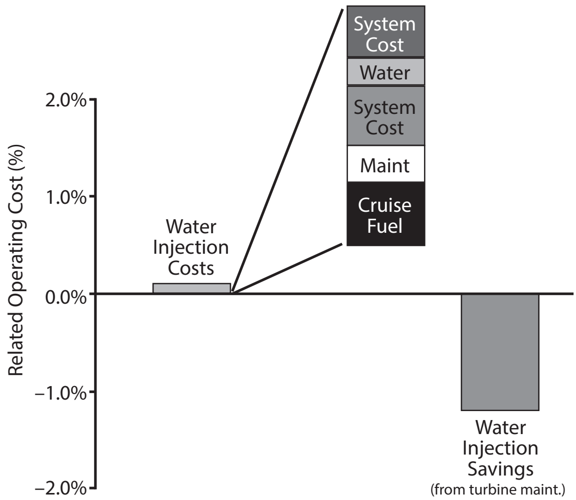

Figure 1
Water injection costs [6]

Water injection is differentiated into two methods, based on the location of injection. These options are compressor or combustor injection. Compressor injection offers two methods: one is a low pressure, the other is a high-pressure compressor injection. The injected liquid can be a water-ethanol mixture that prevents freezing or simply just water. Furthermore, with the help of these above-mentioned injection methods, the mass flow increases and so does the thrust.

As Figure 2 shows, the NOx production progresses rapidly with the increasing combustor inlet temperature.

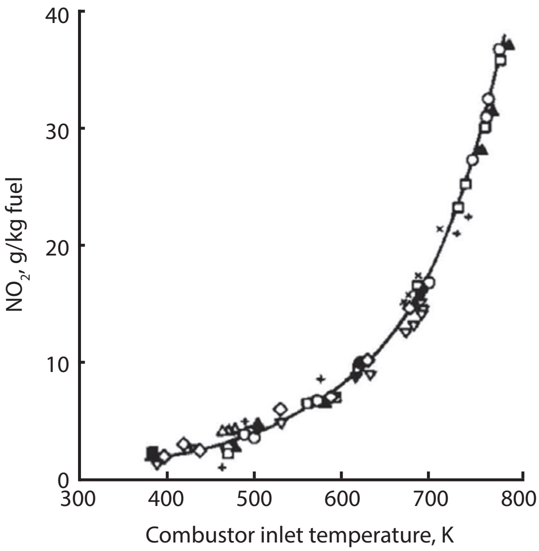

Figure 2
NOx versus combustor inlet temperature [7]

2. Methods

The experiments were performed and evaluated as written in the following paragraphs, beginning with the short description of the turbojet itself, then introducing the modifications that were inevitable to provide water injection.

2.1. The engine

In this study, we used a single shaft TKT-1 jet engine. It is a modified TS-21 Soviet starter gas turbine which was built in the MiG-23 fighter jets, and after several modifications at the department between 2005–2007, it was converted to a jet engine. The cross-section of the engine can be seen below in Figure 3. In terms of gas generator construction, it consists of a centrifugal compressor and an axial turbine. The combustion chamber has a straight-through flow with an annular design, into which 4 nozzles inject the required fuel.

During the conversion to a jet engine, an inlet manifold was installed, which is located vertically to achieve uninterrupted medium intake. The rotor and combustion chamber remained in their original condition; no changes were made here. After the turbine stage, the work turbine and gear housing were removed and replaced by a central cone as well as a diffuser and variable exhaust nozzle. Figure 3 shows the TKT-1 as a jet engine after the transformations. In order to create the required measuring environment, a test bench was built and equipped with additional units and controls for proper operation and measurements [9].

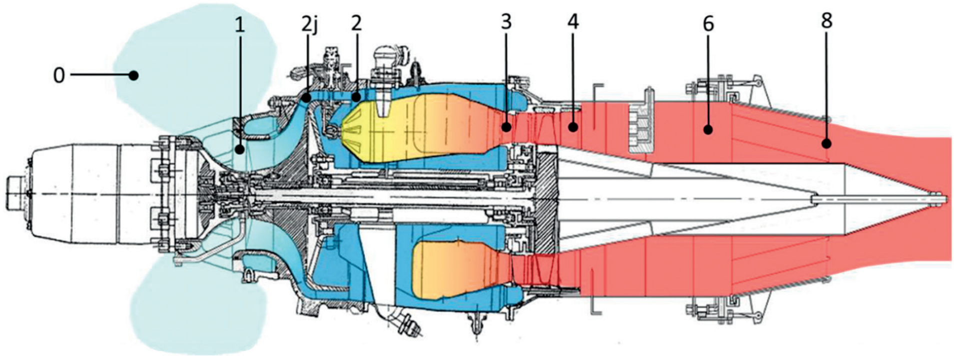

Figure 3
TKT-1 engine. Source: Compiled by the authors.

2.2. Modifications

As this present research aims to study the operation of water injection, it was necessary to build a system that can be used during the measurements.

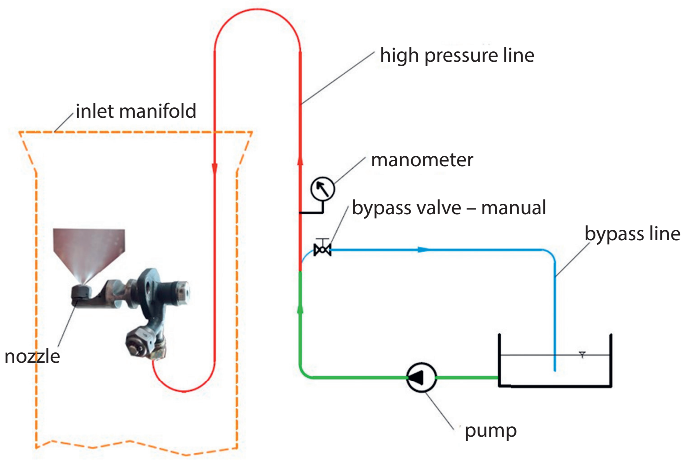

Figure 4
Water injection system. Source: Compiled by the authors.

Consideri ng the design of the engine, injection into the combustion chamber is not possible according to the current possibilities, it requires special nozzles or modification of the entire structure and provision of an additional injection possibility. Consequently, the only option was a direct injection upstream of the compressor, for which the appropriate nozzle had to be placed in the intake manifold so that the small-diameter water droplets vaporised and injected at high pressure are entering the engine together with the intake medium.

The system consists of a high-pressure pump with a nominal pressure of up to 100 bar, connected to the water mains and operating at 230 Volts, an adjustable bypass line, and a manometer, followed by a nozzle. The used nozzle originates from the original TS-21. The plan of the unit is shown in Figure 4.

The pressure upstream of the nozzle is regulated by manually opening or closing the bypass line. This method can be used to set the desired injection pressure.

The nozzle is the TS-21 factory fuel nozzle, one of which is now used for water injection. The nozzle is installed into the inlet manifold through the inlet from above using a metal pipe to which the nozzle is connected. The nozzle was placed in an upward position against the inflowing medium, thus ensuring the homogeneity of the injection and taking advantage of the flow conditions prevailing in the intake manifold, through which the injected water enters the compressor with the outside air medium as shown in Figures 5 a and b.

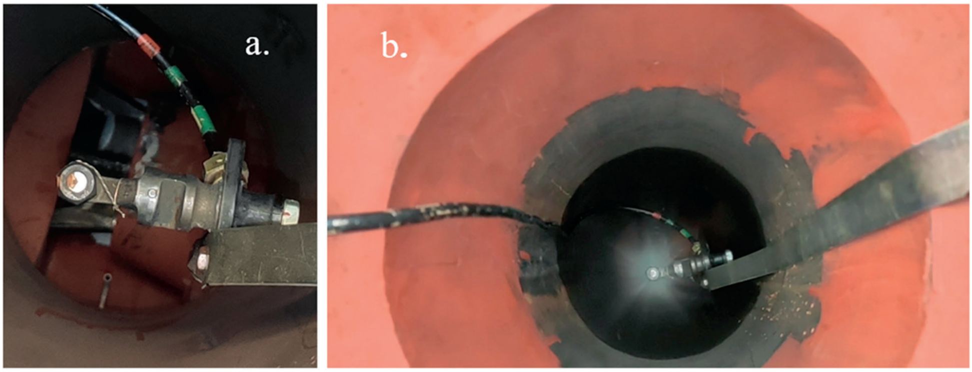

Figure 5
Nozzle installed in the engine intake. Source: Compiled by the authors.

2.3. Experimental determination of the amount of water sprayed

It was necessary to determine how much mass flow the nozzle could deliver to the inlet at a given constant set water pressure. Hence it is installed in the intake manifold, the injection is operated under approximately atmospheric conditions during the engine operation, so the method presented here will provide relevant data for subsequent operations under the same performance conditions. The measurements were taken at pressures set to 30, 40, 50, and 62 bar – which was found to be the practical maximum pressure of the system under the current operating conditions.

The water was collected in a beaker, where the time required for a given volume to flow out was measured, 3 times per pressure, for measurement accuracy. Converting these data to mass flow yielded the values shown in Figure 6 below.

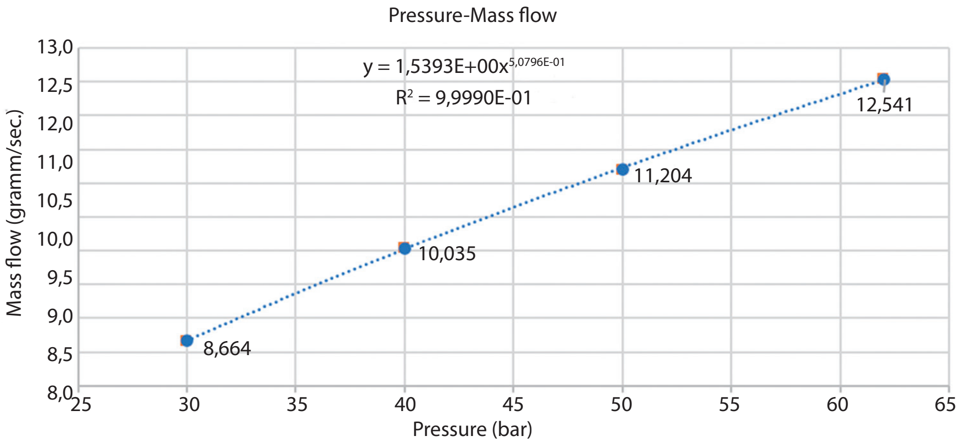

Figure 6
Water mass flow rate. Source: Compiled by the authors.

Next, Figure 7 shows an assembly for measuring the injection volume, which was later installed on the gas turbine test bench.

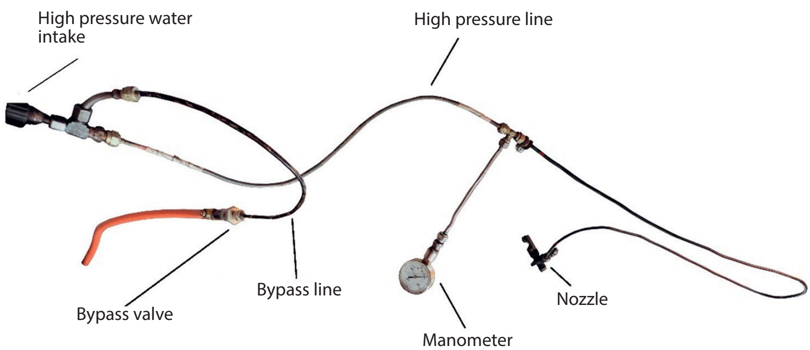

Figure 7
Realisation of the injection system. Source: Authors' own photograph.

3. The experiment

After all the preliminary measurements were taken, the experiment could begin. It is important to mention that the TKT-1 was operated in the yard of the laboratory because currently, the internal equipment of the laboratory does not allow indoor operation. This also affects the measurements through fluctuations in environmental characteristics. The test bench equipped with the water system is shown in Figure 8.

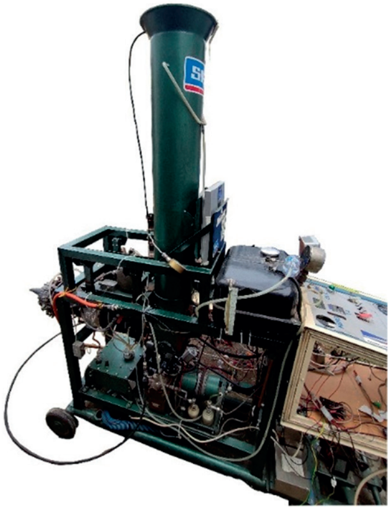

Figure 8
Arrangement of the testbed. Source: Authors' own photograph.

Gas emissions were measured with the use of the Testo 330-1 LL gas analyser with reliable CO (accuracy: ± 5%) and NOx (accuracy: ± 2 ppm) measuring cells.

3.1. The procedure of experimental measurements

At the beginning of the measurement, a data logging program is started, which records the temperature, pressure and flow data measured by the instruments mounted on the engine. The water system is switched off.

After starting the engine, we waited for the values to stabilise. After that when the engine ran smoothly and warmed up it was set to a higher power operating mode. At this point the temperatures and the RPM also increased. With the stabilisation of the operating characteristics (1–2 minutes), the dry operating state began, which served as the basis for the comparison with the wet one.

At the same operating state as the dry one, the high-pressure pump of the water system was started with the fully open bypass line. The desired pressure in the water system was set manually by closing the bypass valve. Data collection of the engine that continues to operate at the set water pressure is still in progress, while the water pressure is recorded by reading the pressure gauge visually and recording the values manually. As the wet operating condition got stabilised, the engine ran for a couple of minutes while the parameters were monitored using a computer.

After the wet operation measurement, water injection was cut off by switching off the high-pressure pump and opening the bypass line manually.

After the measurement, the engine was stopped as well as the data recording program. This was followed by data extraction and evaluation.

4. Calculations

The cycle calculations were performed using the data recorded during the measurement, applying the formulae used in the case of a single-stream turbo engine and basic thermodynamics from [10], [11]. For the calculation, the authors used Microsoft Excel in their research.

The result of the measurement is shown in Figure 9. The vertical lines in the graph indicate the moments of each of the most important events of the operation, which can also be seen on the graph. Highlights of the wet and dry selected sections are illustrated in Figures 10a and b.

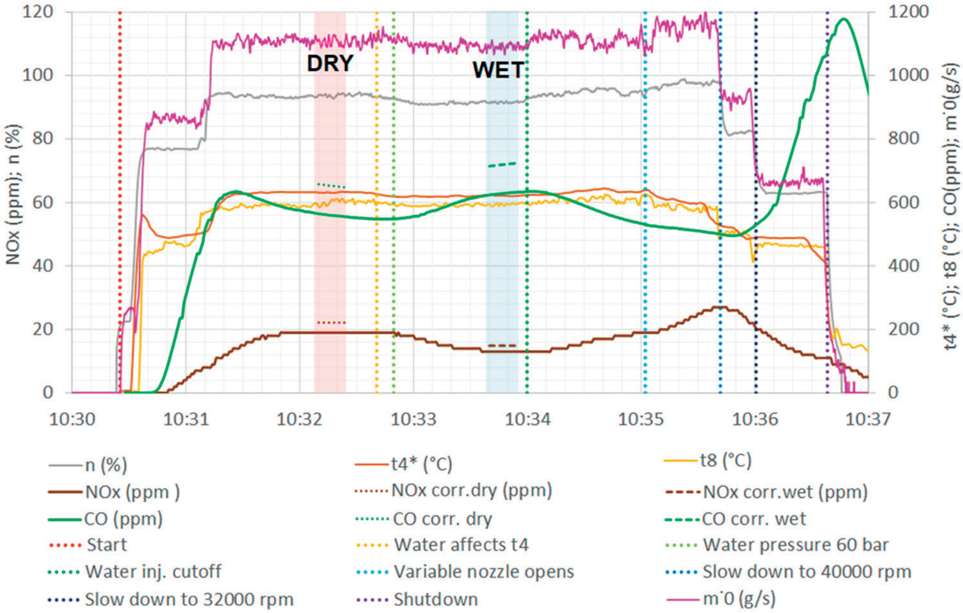

Figure 9
Diagram of experiment parameters. Source: Authors' Excel diagram.

Water injection shows significant changes in each value. Its most striking effect is the marked change in emission values for the whole process, i.e. green and brown lines.

The figure shows the continuous increase and then the stabilisation of the NOx value after the start-up, while the CO value decreases continuously with the stabilisation and improvement of the combustion quality.

With the appearance of water injection, temperatures, as well as engine speeds decrease, resulting in a dramatic reduction in NOx, thus reaching a minimum, while CO emissions began to increase markedly, and got stabilised before the injection was stopped.

As shown above in Figures 10a and b, after stopping the injection, the graphs tend to the values of dry operation again, as the water that may remain inside evaporates. After that, the thrust lever was pulled down in two steps and succeeding approximately half minute idling the engine was shut down.

The continuous emission lines are the raw concentration values recorded by the instrument, which must be converted to the reference oxygen content specified for the specific combustion plant (gas turbine). The corrected values are marked with dotted lines, and they were calculated only for the selected limited periods of dry and wet operations, for comparison.

The measurement of dry operation after start-up and setting the speed at the selected operating position resulted in the values shown in Figure 10a during the test period.

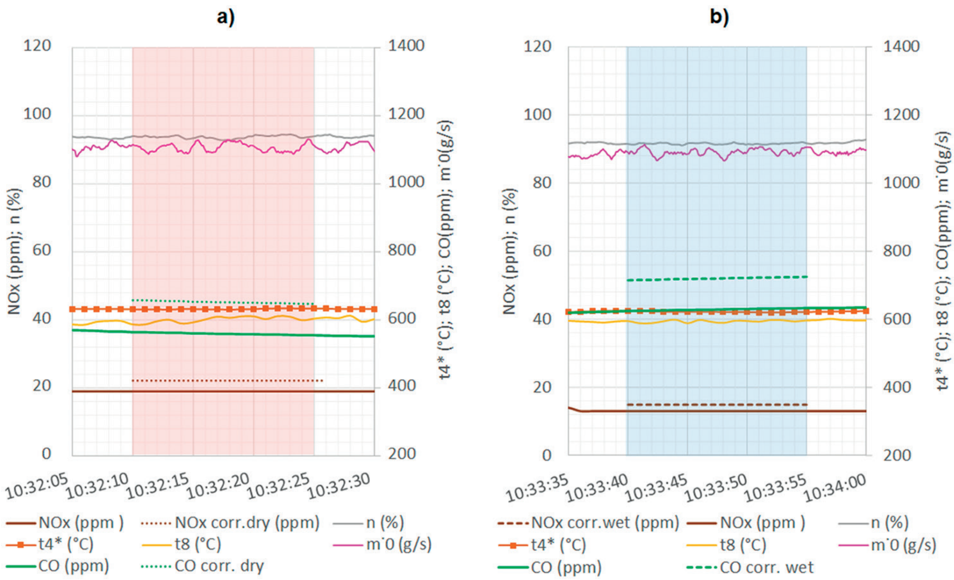

Figure 10
a) Dry operation, b) wet operation. Source: Authors' Excel diagram.

The dry calculations were taken with the values in the highlighted zone. The test time interval for wet operation is shown in Figure 10b. The main performance-relevant characteristics including the changes, are summarised in Table 1.

Table 1
Comparison between dry and wet operational parameters. Source: Authors' Excel diagram.

Parameter	Dry	Wet	Change (%)
T_2^* (K)	473	415.4	–12.18
T_3^* (K)	1,068.5	1,010.2	–5.45
T_4^* (K)	904.5	895.45	–1.00
T_8 (K)	873.37	865.70	–0.88
F_t (N)	303.12	291.63	–3.8
η_t	0.05544	0.05129	–7.48
NOx (ppm)	22	15	–31.8
CO (ppm)	652	733	12.4

In this case, the thrust decreases contrary to expectations, while the thermal efficiency decreases as expected in the wet case. The results of the flue gas measurement provide important information on the emission values. In terms of NOx, there is a considerable difference of 7 ppm between wet and dry operation, which means a 32.9% reduction in emissions. Taking in to account an inaccuracy of 2 ppm, this value is 17.6% in the worst case. There is a 12.4% rise in CO emissions, which means an increase of 81 ppm compared to dry operation.

The results of the measurement show a minimal decrease in thrust, in which winter conditions and the high ambient humidity during the measurements may play a major role, which influences the outcome of the experiment. It is important to note that during the measurement, the fuel supply was constant, i.e. the measurement was concentrated on the effect of the temperature reduction and not on the increase of the thrust. Dry operation should have been repeated with the temperatures measured at the wet operation, which is still less than the maximum, so that its thrust should also be less than in the wet case.

4.1. Theoretical calculation

In the following calculation, it is assumed that the engine operates at the same temperatures as in dry operation, but this time with water injection. As a result, it requires the injection of additional fuel, which leads to a higher temperature, but due to water cooling, it remains within the permissible range, thus making it possible to theoretically calculate the actual thrust-increasing effect of water injection with a simplified model. The assumed values can be seen in Table 2 in the column named "Wet, hot".

Table 2
Theoretical values. Source: Authors' Excel diagram.

Parameter	Wet	Dry	Wet, hot
q_T	0.016902	0.016644	0.018414
Q_{fuel} (l/h)	83.5	82.5	90.9675
$\dot{m}_{fuel}$ (kg/s)	0.018648	0.018425	0.020316
T_3* (K)	1010.2	1068.5	1068.5
T_4* (K)	895.4	904.5	904.5
c_8 (m/s)	259.94	269.34	271.72
T (N)	291.629	303.12	305.3

The results, in this case, are in line with our expectations, the value of c_8 is rising so does the thrust. The fuel mass flow rises a bit. Consequently, this calculation demonstrates the thrust increasing effect of water injection, which was the rudimentary purpose of the study.

5. Conclusion

It can be concluded from the measurement experience, the results and the relevant part of the literature that the current measurement is not able to show the essential part in the field of thrust increase, i.e. what the situation is in hot environment because the essential difference is to be found there. The use of water injection results in a reduction in thrust on its own, but it also greatly reduces the gas temperature. Thus, at high ambient temperatures, the takeoff thrust could only be achieved with more heat than allowed. It results in reduction of the service life of the engine components or can even cause damage. However, by injecting water the thrust can be increased compared to the thrust achievable in the dry case at the maximum permissible gas temperature. This effect can be only seen in the theoretical model.

In terms of emissions, the results are a good representation of the changes due to chemical processes as well as the temperature drop, with the beneficial effect of the injection system on NOx emissions reaching over 30% less pollutant. The increase in CO emissions is due to the imperfect combustion that is inherent in the process, so its value has also developed as expected.

It may also be worth thinking in the direction of optimisation that the water system used in other phases of flight can be operated cost-effectively and efficiently to further reduce emissions due to the cooling and thrust-enhancing effects provided not only in take-off operation. A more comprehensive study should be carried out to determine how effective and economical are the dry emission reduction methods used today, such as TAPS, etc.

5.1. Limitations of the study

Due to slight malfunctions of the measuring equipment, in this study simplification had to be applied in some cases, but more accurate results can be achieved by repairing or replacing the sensors. To measure the thrust more accurately, the currently defective thrust measuring system and the compressor discharge temperature measuring device must be replaced as soon as possible.

Carrying out measurements outdoors leads to further inaccuracies, due to changing weather conditions, therefore the establishment of an indoor measuring test environment could give more accurate results.

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Vízbefecskendezés hatásának kísérleti vizsgálata mikro sugárhajtóművön

A 21. században egyre nagyobb nyomás nehezedik a légi közlekedési ágazatra a károsanyag-kibocsátás növekvő mértéke miatt. A környezetre gyakorolt negatív hatás csökkentése egyre inkább előtérbe került, aminek egyik lehetséges módja az 1960-as években kifejlesztett, akkoriban csupán tolóerő-növelésre használt vízbefecskendezés alkalmazása. A korszerű hajtóművek megjelenésével a vízbeporlasztás teljesítménynövelő hatása iránti igény elmaradt, azonban alkalmazása kibocsátáscsökkentő és szerkezetkímélő hatása miatt napjainkban is alternatívaként szolgálhat. A beporlasztott víz hűtő hatása szerepet játszik a hajtóműkomponensek élettartamának növelésében is, ami a karbantartási és üzemeltetési költségek csökkenéséhez vezethet. Munkánkban a vízbefecskendezés teljesítményre és kibocsátásra gyakorolt hatását vizsgáltuk a TKT-1 kísérleti gázturbinás sugárhajtóművön. A próbapadon eszközölt módosításokkal lehetőség nyílt a szívócsatornában elhelyezett fúvókás vízbefecskendezéses üzem méréseinek elvégzésére. A kapott eredmények alapján a tolóerő-növelő hatás a kísérleti környezeti viszonyok, valamint a rendszer kiforratlansága miatt nem valósult meg, azonban a kibocsátások és gázhőmérsékletek redukálásának terén a vízbefecskendezés eredményesnek bizonyult. Az egyes keresztmetszetekben mért gázhőmérsékletek csökkenésének szerkezetre gyakorolt jótékony hatása mellett, a nagy környezeti terhelést jelentő NOx-gázok emissziója is nagy mértékben, 30%-kal csökkent a száraz üzemhez képest.

Kulcsszavak: *emisszió, tolóerő-növelés, vízbefecskendezés, mikro gázturbina, sugárhajtómű*

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