Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(1), 148–159
https://doi.org/10.12913/22998624/195236
ISSN 2299-8624, License CC-BY 4.0

Received: 2024.07.12
Accepted: 2024.11.15
Published: 2024.12.01

Comparison and mathematical modeling of surge avoidance methods in turbojet engine compressor

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ABSTRACT

The sudden surge phenomenon in an axial compressor represents one of the most critical issues that can confront a turbojet engine. This phenomenon primarily arises from the engine ingesting hot exhaust gases from weaponry systems, particularly in military aircraft, potentially leading to engine failure. This study delves into the impact of hot gas ingestion on compressor stability and compares a range of effective methods to prevent surge in such cases which are: (1) air bleed from the compressor, (2) fuel cut-off, (3) gas cooling through water injection at the air inlet. The R29-300 twin-spool turbojet engine was chosen for computational experiments due to the availability of the necessary digital information for mathematical modelling of this engine. It is a two-shaft turbojet engine consisting of a low-pressure compressor (5 stages), a high-pressure compressor (6 stages), an annular combustion chamber, a high-pressure turbine (two stages), and a low-pressure turbine (one stage). The results showed that introducing gases with a heating rate of up to 5000 Kelvin per second causes the low-pressure compressor to exit its stable operating regime and the engine to stall. The effect on the high-pressure compressor was minimal and did not exceed the stability limits, therefore the focus of the procedures was on the low-pressure compressor. The results also showed that both methods 1 and 2 are effective in preventing surge within an acceptable stability range, but they have several drawbacks, including a decrease in engine thrust and efficiency. On the other hand, the water injection method eliminates the root cause of surge by cooling the incoming gases and maintains engine stability. The amount of water required for this process is relatively small and can be carried on aircraft without a significant impact on weight and volume.

Keywords: turbojet engine, compressor, surge, stability, air bleed, injecting water.

INTRODUCTON

Surge is considered one of the most critical and dangerous problems afflicting turbojet engine, serving as a primary cause of numerous aviation accidents, especially in turbojet engines equipped with axial compressors. Surge is defined as a series of violent pressure and velocity oscillations that occur in the axial direction of the compressor with such intensity that reverse flow is induced, happening over a short period of time and leading to engine failure if appropriate measures are not taken [1].

There are several factors that can lead to the occurrence of surge, including flight at high altitudes and speeds outside the engine's operating limits, which can result in sudden changes in pressure at the engine inlet or increased inlet air temperature due to aerodynamic heating caused by shock waves formation at the inlet. The most critical issue leading to sudden and violent surge is the ingestion of hot exhaust gases emitted during the firing of cannons or missiles in military aircraft. A set of control methods to counteract surge has been implemented. These include bleeding air from the intermediate stages of the compressor, where excess air is discharged through openings formed around the periphery of the compressor stage to the outside of the engine. Another method involves controlling the fuel flow rate by partially or completely cutting off the fuel supply to the engine. These systems are controlled by an automated control system that predicts surge occurrence through engine and aircraft sensors, and are also linked to the weapon and missile firing button in military aircraft [2].

Numerous studies have been conducted in the field of cooling the inlet airflow to turbojet engine by injecting water. The aim of these studies is to expand the flight envelope of aircraft by overcoming the limitations of Mach number [3], or to achieve more efficient turbojet engines by reducing specific fuel consumption and increasing thrust using water injection technology [4, 5], or to increase the altitudes and speeds that exceed the basic operational limits of the turbojet engine [6]. Previous studies have shown the theoretical effectiveness of this method, but the main problem in its application is that using this technology to achieve the aforementioned goals requires a relatively long period of time, which in turn leads to the consumption of large quantities of water that are difficult to carry on the aircraft due to their large volume and weight. In this study, the use of water injection technology is proposed to mitigate the adverse effects of hot gas ingestion by the turbojet engine (leading to compressor surge) due to the effectiveness of this technique and the fact that the required time for its application is limited (surge transit time) and requires a limited amount of water that can be easily carried on board the aircraft. This method is compared with previous methods applied to the R29-300 engine.

Turbojet engines overview

The turbojet engine stands as one of the most significant technological advancements of the 20th century. Its evolution, characterized by enhanced performance, safety, and economic efficiency, has revolutionized transportation, travel, commercial operations, and even military arms races. Air traffic has witnessed an average annual growth rate of around 5%. However, the negative environmental impacts of global air travel have imposed significant challenges on the development and manufacturing of jet engines [7].

Turbojet engines, in general, are composed of the following primary components: air intake, compressor, combustion chamber, turbine, exhaust. as shown in Figure 1 [8];

The jet engine operates on the Brayton cycle, a closed-loop thermodynamic cycle composed of four processes, as depicted in Figure 2:

- compression process (1–2) – it takes place mainly in the compressor and in the air inlet;
- heating process (2–3) – it takes place within the combustion chamber under constant pressure;
- expansion process (3–4) – it takes place in the turbine and the jet pipe.

The cooling process (4–1) is replaced by exchanging the working gas through the introduction of a new air stream [9, 10]. Jet engines operate on the principle of reaction propulsion.

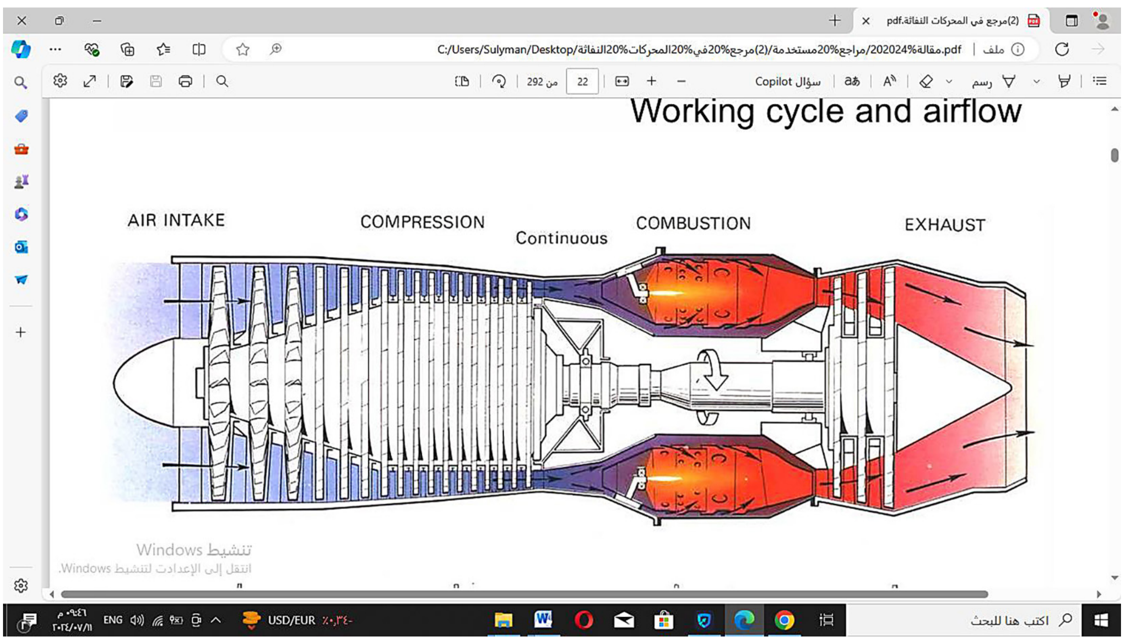

Figure 1. Turbojet engine components [8]

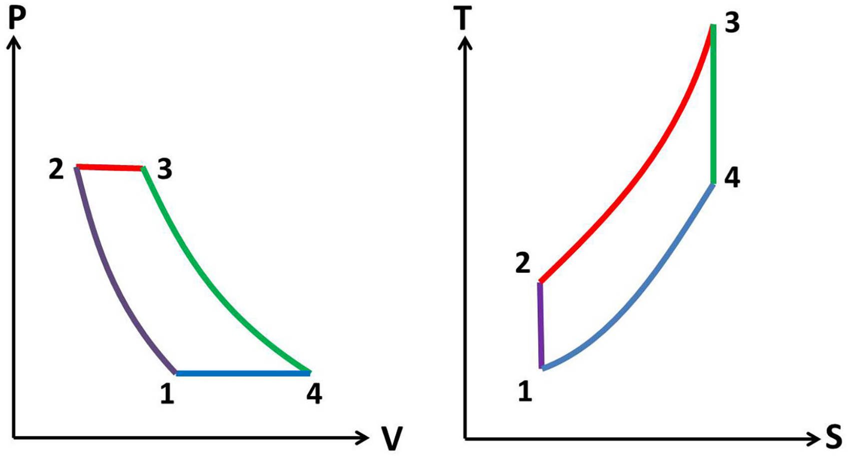

Figure 2. Brayton cycle

The airflow enters the compressor through the air inlet, where it is compressed and sent to the combustion chamber. In the combustion chamber, the high-pressure air is mixed with fuel and ignited, resulting in a continuous combustion process that heats the gas mixture to extremely high temperatures. This hot, high-pressure gas then expands through the turbine, extracting energy to drive the compressor. The remaining energy is converted into thrust as the gases exit through the exhaust nozzle [8, 11].

Axial compressors

In the realm of jet engines, two primary types of compressors are employed: centrifugal compressors and axial compressors. While both contribute to the engine's performance, axial compressors have emerged as the dominant choice for modern jet propulsion systems [8].

Axial compressors are composed of a series of stages, each with a similar design and operation. In each stage, the airflow is compressed partially with a small compression ratio. The compression processes are repeated from stage to stage until the desired high pressure ratio is achieved, with a possible maximum of 20 stages. Consequently, the number of stages in the compressor depends on the required pressure ratio [12, 13].

Each stage in an axial compressor consists of a row of rotating blades mounted on the stage's hub, which rotate with the hub, followed by a row of stationary blades mounted on the stationary casing of the stage. These stationary blades do not rotate with the stage. The task of rotating blades, lies in imparting mechanical energy to the airflow passing through them. This transfer of energy leads to an increase in both the pressure and kinetic energy of the airflow. In contrast, stator blades convert the kinetic energy gained by the airflow from the rotating blades into potential pressure energy. In addition to the aforementioned, rotating and stator blades guide the airflow at appropriate angles towards the subsequent row of blades [13, 14].

Axial compressors operate over a broad range of both converted rotational speed and converted airflow, as well as compression ratio. Each converted rotational speed corresponds to an appropriate compression ratio and airflow rate. The stable operating regime of an axial compressor within an engine system (characterized by the compression ratio P_{ik} and airflow rate G_R at each converted rotational speed n_c) is represented by a point on the compressor map. The locus of these points at different converted rotational speeds defines the compressor's stable operating line. The following figure illustrates the operating line on a compressor map

The red line in Figure 3 represents the compressor's unstable operating line. If the operating point of the compressor moves above this line, the compressor enters a surge condition, leading to engine stall and potentially severe damage to the compressor. The green lines in Figure 3 represent different converted rotational speeds of the compressor. The blue line connecting points H and B represents the optimal combined operating line for the compressor in relation to the entire engine, aligning with the operation of the other engine components. The operating line is constrained by the control system to a rotational speed range greater than $n_{C,H}$ and less than

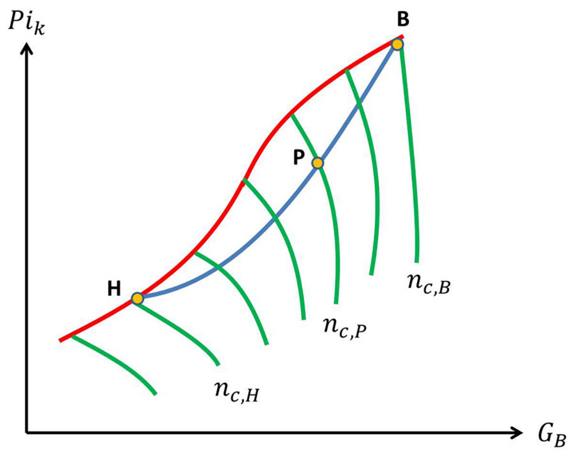

Figure 3. Compressor map

$n_{C,B}$. This line indicates the operating points that achieve the best pressure ratio and airflow rate for each converted rotational speed for the entire engine. Operating along this line ensures efficient and effective engine operation [15].

The stability of an axial compressor, defined as the distance of its operating regime from the instability region, can be quantitatively evaluated by comparing the ratio of both compression ratio and airflow rate at the stability boundary (Point F in Figure 3) to their corresponding values at the operating point (Point P in Figure 3). This relationship is expressed as follows:

$$K_u = \frac{\left(Pi_k/G_B\right)_F}{\left(Pi_k/G_B\right)_P} \tag{1}$$

This ratio is referred to as the compressor stability factor. The stability index can also be expressed as a percentage, referred to as the stability margin DK_u[15].

$$DK_u = (K_u - 1) \cdot 100\% \tag{2}$$

The unstable operation of the compressor is caused by the instability of the operation of its stages or some of them, on the one hand, and by the incompatibility of the operation of the stages, resulting from the effect of the axial velocity of the flowing stream on these stages when they work together in the compressor. A decrease in axial velocity, which corresponds to a reduction in airflow rate, below the optimal value leads to an increase in the angle of attack of the airflow on the later stages of the compressor. Consequently, these later stages are more likely to experience instability before the other stages. Since the later stages of the compressor have shorter blades, the separation phenomenon (flow separation) that occurs on these stages is more violent. This violent separation significantly reduces the airflow rate and, consequently, the axial velocity, across all compressor stages. In turn, this reduction in axial velocity further increases the angles of attack on all stages, pushing them into unstable operation. Therefore, the onset of separation on any of the later stages rapidly propagates (within fractions of a second) to all other stages of the compressor, causing the entire compressor to enter an unstable operating regime. As a result, the operating point of the compressor abruptly shifts to the unstable region on the compressor map [14, 16].

Regions of airflow separation that encompass a 'large' portion of the compressor, unify across all stages, and rotate at a relatively low relative speed. This will naturally lead to a significant reduction in airflow, efficiency, and compression ratio. Moreover, exiting this state is challenging and is achieved by reducing the resistance on the compressor outlet through special procedures (such as cutting off fuel to the engine, and air bleed valves on the compressor). In practical situations, another form of instability can occur, known as ' surge.' This type of instability differs from the one described previously in that the pressure and flow oscillations are more violent; they affect the entire airflow path connected to the compressor (i.e., the engine); the number of oscillations per second is higher; and it can lead to engine failure [16, 17].

Impact of high inlet air temperature on turbojet engines

One of the most significant and hazardous conditions that a turbojet engine can encounter is an increase in inlet air temperature. This rise in temperature can result from either high-altitude, high-speed flight or the ingestion of hot exhaust gases from weapons in the case of military aircraft [3,18]. The following relationship expresses the joint operation of the engine components:

$$\frac{Pi_k}{q_l} = A \cdot \sqrt{\frac{T_G}{T_B}} \tag{3}$$

where: A – a numerical constant related to the compressor's characteristics, q_l – airflow line density, T_B – inlet temperature to the compressor, T_G – outlet temperature from the combustion chamber.

The introduction of hot gases through the air inlet leads to a change in the inlet temperature T_B.

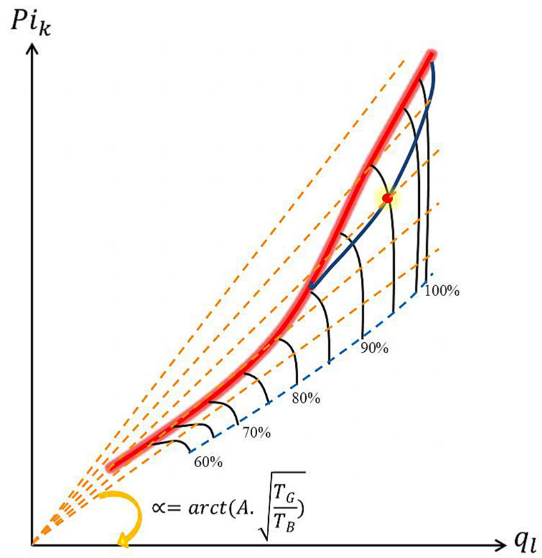

Figure 4. The effect of increasing factor ∝ on compressor stability

This temperature change subsequently affects the temperature of the various engine sections, resulting in a sudden huge increase in the gas temperature T_G.

As the relationship indicates, an increase in the temperature at the combustion chamber exit T_G leads to an increase in the factor $\frac{Pi_k}{q_l}$. This factor represents Arc tan of the angle formed by the line connecting the origin to the operating point on the compressor map, as shown in the figure 4 [15].

$$\propto = arct(A \cdot \sqrt{\frac{T_G}{T_B}}) = arct(\frac{Pi_k}{q_l}) \qquad (4)$$

This unstable condition occurs when there is a rapid increase in T_G, which leads to a decrease in DK_u and causes the compressor to stall. In severe cases, as the engine swallowing hot gases it can even lead to surge phenomenon. Conversely, a decrease in temperature T_G leads to an increase in the stability margin. Therefore, When T_G rises as a result of the engine swallowing hot gases, fuel cut-off (either complete or partial for fractions of a second) is employed to prevent the compressor from entering unstable operation when surge phenomenon [2, 15]. In addition, it may cause corrosion of the turbine blades [19].

There exists a range of solutions to prevent the compressor from entering into unstable operation. These include: Change the cross-sectional area of the nozzle exit area, Compressor Bleed method, A method of reducing or cutting off fuel for fractions of a second, Method of cooling gases before reaching the compressor's final stages by injecting water into the compressor. In the following section, the effect of the aforementioned methods on engine performance stability will be studied and compared.

MATERIALS AND METHODS

The R29-300 twin-spool turbojet engine was chosen for computational experiments due to the availability of the necessary digital information for mathematical modeling of this engine. It is a two-shaft turbojet engine consisting of a low-pressure compressor (5 stages), a high-pressure compressor (6 stages), an annular combustion chamber, a high-pressure turbine (two stages), and a low-pressure turbine (one stage). The most important parameters for this engine are given in Table 1 on the computational system: These parameters are derived from the design and experimental records of the R29-300 engine and are calculated at maximum computational operating system and under standard atmospheric conditions. Through these parameters, the compressor map is determined using similarity parameters, making it a general characteristic for all engine operating systems. Among the most important similarity parameters used are the Converted rotational speed, n which are defined by the following relationship:

$$n_c = n \cdot \sqrt{\frac{288}{T_B}} \qquad (5)$$

The foundation of the mathematical model that describes transient processes in the engine is the equation of motion for the rotating part (which is the equation of rotation of a rigid body about an axis passing through its center):

$$J \cdot \frac{d\omega}{dt} = \sum M \qquad (6)$$

where: M – the torque acting on the rotating shaft, ω – the angular velocity of the rotating shaft, J – the polar moment of inertia of the rotating shaft.

This equation applies to both the low-pressure rotating axis (ND) and the high-pressure rotating axis (BD):

$$\frac{dn_{ND}}{dt} = \frac{900}{\pi^2 \cdot J_{ND} . n_{ND}} (N_{TND} - N_{kND}) \qquad (7)$$

Table 1. Necessary parameters of the twin-axial turbojet engine R29-300

Compression ratio of high pressure compressor pi_{KBD}	3.53
Compression ratio of low pressure compressor pi_{KND}	3.72
Air flow G_B	120 kg/s
Maximum temperature T_G	1420 k
Expansion ratio in the turbine pi_T	3.1
Rotation speed of high pressure shaft n_{BD}	8599 r.p.m
Rotation speed of low pressure shaft n_{ND}	8333 r.p.m
Push power P	82000 N
Fuel consumption G_T	2.5

$$\frac{dn_{BD}}{dt} = \frac{900}{\pi^2 \cdot J_{BD} \cdot n_{BD}} (N_{TBD} - N_{kBD}) \quad (8)$$

where: n_{ND}, n_{BD} – rotational speed of the low-pressure compressor shaft and the high-pressure compressor shaft, respectively (r.p.m), J_{ND}, J_{BD} – polar moment of inertia of the low-pressure compressor shaft and the high-pressure compressor shaft, respectively (kg·m^2), N_{TND}, N_{kND} – power of the low-pressure compressor and the low-pressure turbine, respectively (W), N_{TBD}, N_{kBD} – power of the high-pressure compressor and the high-pressure turbine, respectively (W).

A computer simulation program was designed to describe the stability of the engine compressor using the Visual Basic programming environment. This program relied on the compressor's virtual maps and parameters taken from the reference R29-300 turbojet engine database. It also utilized the differential equations for the engine's rotating part, the engine stability equation, and the thermodynamic calculation equations for the gas turbine engine in engine theory [20]. The boundary conditions were set according to the assumed test point, which corresponds to standard atmospheric conditions at sea level (P= 101325 Pa, T = 288 K) and the engine's maximum operating condition as specified in Table 1.

Calculation of turbojet engine stability index during hot gases ingestion

The following figure illustrates the time-dependent temperature change as hot gases enter the engine. The gas effect passes through four stages (and the data will be entered into the mathematical model in four stages)

- Stage 1 – constant temperature (before entry of hot gases).
- Stage 2 – rapid temperature increase at a rate of 5000 K/S (due to hot gas entry) And during the transit time of (0.029 S).
- Stage 3 – rapid temperature decrease at a similar rate.
- Stage 4 – return of temperature to normal value.

The change in temperature in the second and third stages is on a parabolic curve, but it was considered linear due to the short time period of the effect and to facilitate the study.

Several calculations were performed to determine the effect of critical temperature rise on

Table 2. Polar moment of inertia values of low pressure compressor shaft and high pressure compressor shaft (J_{ND}, J_{BD})

Injecting water into the air intake	Cutting off fuel (100%) for fractions of a second	Reducing off fuel (50%) for fractions of a second	Air bleed from the compressor	After the entry of hot gases	Before the entry of hot gases	Parameters
9.3	6.1	4.9	10.7	3.9	9.3	$DK_{u(KND)}$
16	38.17	24.41	11.58	14.36	16	$DK_{u(KBD)}$
1420	1220	1487	1798	1717	1420	TG
3.72	3.32	3.36	3.24	3.42	3.72	Pi_{KND}
120	91	91	92	92	120	G_B
8333	8330	8344	8365	8358	8333	n_{ND}

compressor stability. The unstable operation of one of the compressors leads to engine instability, as the heating rate due to the engine's ingestion of hot gases reaches 5000 K/s (which occurs during the launch of solid-fueled rockets, as well as when ingesting the exhaust gases of another aircraft). The simulation results are shown in Figure 6.

Figure 6 illustrates the movement of the operating point as hot gases are ingested (during the second stage in Figure 5) and move across the compressor map from position 1 to position 2. As a result of the change in the operating point, the stability margin of the high-pressure compressor decreases, but the operating point remains within the stability limits. However, the low-pressure compressor is more affected (as it is located at the front) where the operating point moves away from the stability limits, causing the compressor to enter the unstable operating region and leading to surge and engine stall.

Methods for compressor control to prevent unstable operation

To prevent unstable operation, also known as surge or stall, in axial compressors, various control methods can be implemented. These methods aim to maintain the compressor's operating regime within its stable limits and prevent the boundaries of instability from being exceeded. The results of applying and comparing three methods will be analyzed and

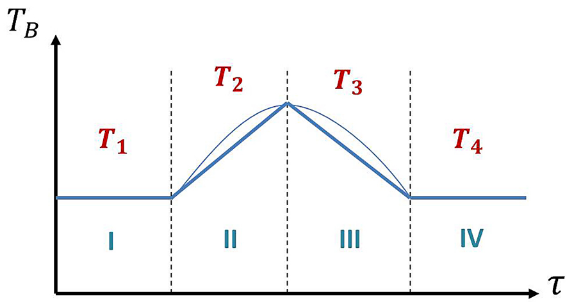

Figure 5. Time-dependent temperature change upon entry of hot gases

calculated: air bleed from the compressor, fuel cut-off, and water injection into the air inlet.

Air bleed from the compressor

This method is considered an effective approach for controlling axial compressors and maintaining their operation within stable limits. When the engine ingests hot gases, the heating rate (τ) increases significantly, and the gas volume expands. Consequently, the downstream components of the compressor are unable to pass the same flow rate that passes through the compressor [16]. This leads to the compressor "adapting" by reducing the axial velocity of the flow and increasing the blade angle of attack. This causes the compressor to enter an unstable operating state known as surge or stall. If a portion of the

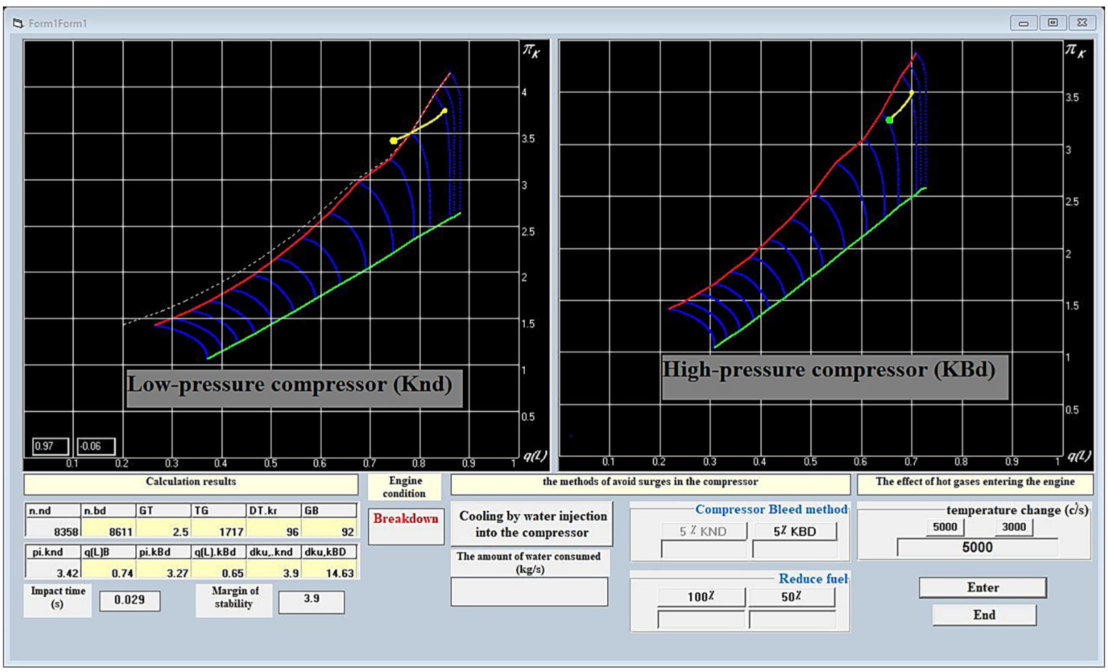

Figure 6. Program results under the engine's operating conditions when hot gases enter

air flowing through the compressor (excess air) is vented to the external atmosphere or to the discharge nozzle, the axial velocity of the flow increases compared to the moment before the vent. This leads to stabilization of the angles of attack and ensures stable operation of the compressor.

In this case, venting air leads to an increase in the stability margin of the low-pressure compressor. Its effect on the high-pressure compressor is limited, and therefore it may suffice to vent air only from behind the low-pressure compressor (or from behind both compressors). In the case of the engine under study, air is bled from the middle stages of the low-pressure compressor [15].

$$G_B = 0.0404 \frac{P_B}{\sqrt{T_B}} \cdot F_B \cdot q_l \tag{9}$$

where: (F_B) – cross-sectional area in front of the compressor.

This equation expresses the air flow relationship G_B related to the Airflow lines density function q_l. Equation 8 indicates that a decrease in G_B (mass flow rate) leads to a decrease in q_l. In addition to a relatively significant decrease in the overall compression ratio of the compressor P_{ik}. Consequently, the value of factor α, which represents the position of the operating point on the compressor map, also decreases. This, in turn, causes the operating point on the compressor map to move closer to the stability boundary. Figure 7 illustrates the simulation results when applying the bleed air method from the low-pressure compressor (during the entry of hot gases). This leads to a decrease in the rotational speed of the low-pressure compressor and prevents the operating point from exiting the stable operating region, ensuring stable engine operation.

Reducing or cutting off fuel for fractions of a second

Reducing or cutting off fuel to the engine for a fractions of a second significantly decreases the thermal resistance at the compressor outlet, leading to improved compressor stability. This can be inferred from Equation 3 and Figure 4. As the temperature at the compressor outlet, T_G, decreases, the angle α, which represents the position of the operating point on the compressor map, also decreases. This implies that the operating point moves away from the stability boundary towards the right on the compressor map, resulting in an increase in the stability margin. As illustrated in Figure 8, the fuel cut-off and restoration process is executed in the following: stages:

- Stage 1: Constant fuel flow rate (before hot gas entry),
- Stage 2: partial or complete fuel cut-off (hot gas entry),
- Stage 3: fuel cut-off (short duration t=0.03 S).
- Stage 4: fuel reintroduction (matching cut-off rate),
- Stage 5: return to normal fuel flow rate.

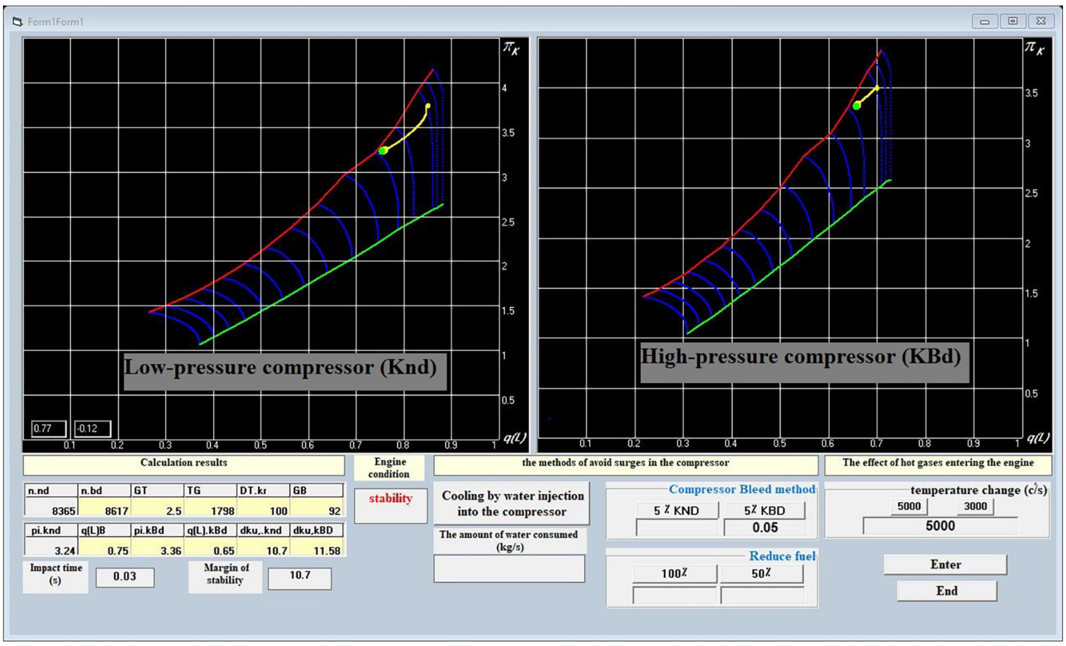

Figure 7. Effect of Air Bleed from the low-pressure compressor on the operating point

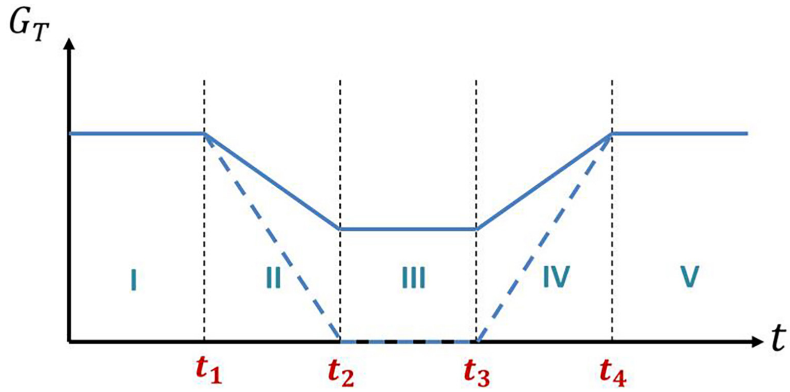

Figure 8. Stages of reducing or cutting off fuel to the engine

The solid line in Figure 8 represents a partial fuel cut, while the dashed line represents a full fuel cut. The duration of phases two and four is linked to the response time of the control system connected to the weapon firing button. The simulation is conducted according to Stage three (Figure 8) and Stage two (Figure 5). Figure 9 presents the simulation results for applying the fuel cut-off method (during hot gas ingestion). This method leads to a decrease in the low-pressure compressor's rotational speed and an increase in the compressor stability margin. The compressor stability level reaches Dku = 6.1 when fuel is cut off during hot gas ingestion. This acceptable value prevents the compressor from experiencing surge and maintains stable engine operation. Therefore, the fuel cut-off method is an effective way to prevent surge.

Cooling of hot gases entering the engine by injecting water into the air intake

In this study, it is proposed to use water injection technology to avoid the negative impact of hot gas ingestion by the turbojet engine due to the effectiveness of this technology and the fact that the required time period for its use is limited and requires a limited amount of water that can be easily carried on the aircraft.

The amount of cooling water required is determined after identifying the quantity of gases that need to be cooled. This calculation depends on the volume of hot gases entering the engine, their inlet time (which is very short), their temperature, and their specific heat capacity. The need for these qualitative data, which are not

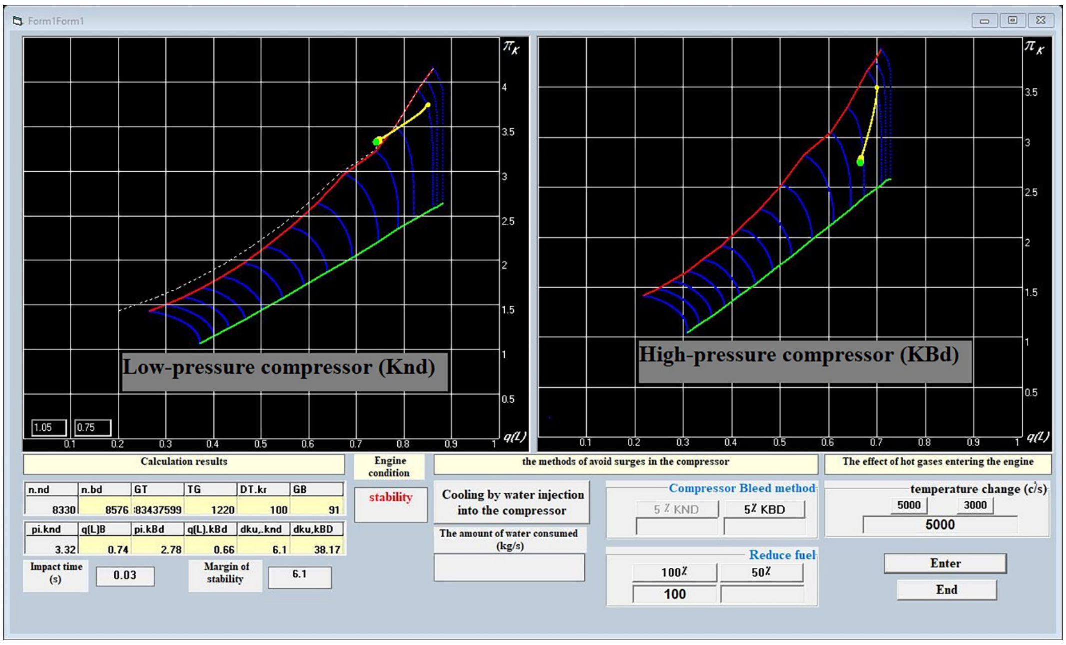

Figure 9. Calculation of engine stability upon introduction of hot gases and complete fuel cut-off for a fraction of a second

accurately available, can be overcome according to the following idea:

Hot gases are mixed with the inlet air entering the engine, and the mixture reaches the compressor at a temperature of Tmax. This is on the one hand, and on the other hand, the amount of gases enters the engine in the form of a 'hot pulse' that lasts for a short period of time not exceeding t=0.05 seconds [1]. Based on the above, the approximate amount of gas that needs to be water-cooled (ΔG_B) can be calculated using the following relationship:

$$\Delta G_B = G_{B0} \cdot t \qquad (10)$$

where: GB0 – maximum engine airflow (kg/s), t – time for hot gases to pass through (s).

Based on this, the amount of heat contained in this gas flow is calculated considering the specific heat capacity of the gas mixture to be an estimated Cp =1.5 kJ/(kg·°C):

$$Q = C_P \cdot \Delta G_B \cdot (T_{max} - T_{min}) \qquad (11)$$

The amount of distilled water required for cooling can be calculated assuming that the water will evaporate and considering the latent heat of vaporization to be 2350 kJ/kg:

$$G_W = \frac{Q}{2350} \qquad (12)$$

Figure 10 illustrates the impact of water injection into the air inlet on engine stability during hot gas ingestion. It is observed that this method almost completely eliminates the negative effect of hot gas ingestion and maintains engine stability when subjected to hot gas ingestion. The operating point remains within the stable operating range and is not affected by hot gas ingestion due to the cooling of the gases before they reach the compressor, thus eliminating the negative thermal impact on the compressor.(The injected water quantity is relatively small compared to the airflow rate during the short time period defined for surge occurrence. Therefore, the impact of the small increase in airflow rate was neglected,, and the focus was placed on the primary effect of the cooling process).

Analysis of results

Utilizing the previously established relationships and engine thermodynamic equations, a set of parameters was calculated before the entry of hot gases, after their entry, and following the application of the aforementioned methods, as summarized in Table 2. The calculations encompassed the following important parameters: T_G – temperature at the turbine inlet, $DK_{u(KBD)}$ – stability margin of the high-pressure compressor, $DK_{u(KND)}$ – stability margin of the low-pressure compressor, G_B – airflow rate, Pi_{KND} – low-pressure compressor compression ratio, n_{ND} – rotation speed.

The ingestion of hot gases by the turbojet engine leads to severe consequences in the form of the phenomenon of " surge " and can even result

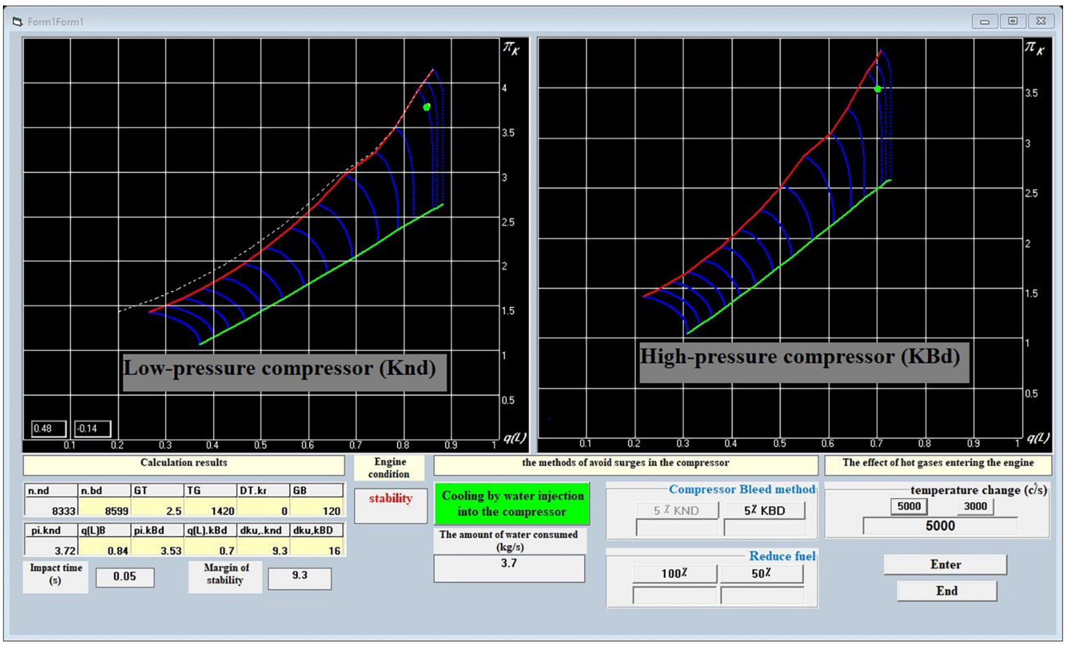

Figure 10. Calculation of engine stability when hot gases enter and water injection method is used at the air inlet

Table 3. Values of critical parameters for a turbojet engine before and after a surge event, along with the corrective actions taken

Injecting water into the air intake	Cutting off fuel (100%) for fractions of a second	Reducing off fuel (50%) for fractions of a second	Air bleed from the compressor	After the entry of hot gases	Before the entry of hot gases	Parameters
9.3	6.1	4.9	10.7	3.9	9.3	$DK_{u(KND)}$
16	38.17	24.41	11.58	14.36	16	$DK_{u(KBD)}$
1420	1220	1487	1798	1717	1420	TG(K)
3.72	3.32	3.36	3.24	3.42	3.72	Pi_{KND}
120	91	91	92	92	120	G_B (kg/s)
8333	8330	8344	8365	8358	8333	n_{ND}(r.p.m)

in engine failure. This is caused by the operating point on the compressor map moving into the unstable operating region. As shown in Table 2, the stability index for the low-pressure compressor drops significantly to $DK_{u(KND)} =$ 3.9, reaching the breakdown stage, while the stability margin for the high-pressure compressor is not significantly affected and remains within the stability range at $DK_{u(KBD)}$ = 14.63. Therefore, the methods used to solve the problem focus on the low-pressure Compressor.

Regarding the air bleed method from the compressor:

The air bleed method is considered an effective technique for enhancing compressor stability when hot gases enter and preventing it from entering the unstable operating region. However, it has several negative consequences, including:

- decreased engine efficiency – the bled air has already consumed work for compression, which is then wasted. This leads to a reduction in engine efficiency;
- reduced compression ratio and airflow rate – the air bleed method results in a decrease in both the compression ratio and airflow rate;
- increased air temperature at turbine inlet – due to the reduced amount of air subjected to the same heating process, the air temperature at the turbine inlet increases. This negatively impacts the turbine blades.

Overall, the air bleed method, while effective in improving compressor stability, comes at the cost of reduced engine efficiency, lower compression ratio and airflow rate, and higher turbine inlet air temperature.

For the fuel cut-off and restoration method applied in fractions of a second, fuel cut-off at 50% was studied. The results showed an improvement in the stability margin of the low-pressure compressor ($DK_{u(KND)}$ = 4.9), which is within the stable operating range. The temperature at the turbine inlet (TG=1487 K) is also acceptable. These values are considered acceptable to overcome the surge phenomenon.

Fuel cut-off at 100% shows a greater improvement in engine parameters, as shown in Table 2. However, one of its drawbacks is that it protects the compressor from surge but with a small stability margin, in addition to the possibility of extinguishing flame in the combustion chamber.

Since the primary issue causing instability and surge is the sharp rise in the temperature of the gases entering the engine, it was proposed to cool these gases using a water injection system within the air intake. While previous methods have focused on avoiding the impact of the high temperature of the incoming gases, this method eliminates the impact from the outset. However, one of the main drawbacks of this method is the entry of water droplets and their collision with the compressor blades, which can lead to blade erosion and surface roughness changes. This drawback can be mitigated by employing a water injection system that ensures optimal spray distribution and small water droplet size to guarantee complete evaporation of the injected water. The study has shown that the required amount of water for cooling and restoring the air stream temperature to its initial value before the entry of gases is approximately 3.7 kg/s, given that the air transit time does not exceed 0.05 seconds and the continuous gas inflow does not exceed 1 second.

RESULTS

The ingestion of hot gases by turbojet engines is considered a dangerous transient condition that can lead to engine surge and potentially catastrophic engine failure if not addressed appropriately. The primary cause of this phenomenon is the high temperature rise of the air at the engine inlet, which in turn increases the heating rate throughout the engine's sections.

Several solutions are employed to mitigate this phenomenon, the most prominent of which are compressor bleed and fuel cut-off. These methods are effective in maintaining engine stability and preventing engine failure, but they come with certain drawbacks, including a reduction in engine thrust and efficiency.

The water injection technique at the engine air inlet is considered an effective method to completely eliminate the impact of this phenomenon. The amount of water required for this process is relatively small and can be carried on aircraft without a significant impact on weight and volume.

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