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THE ADVANTAGES OF USING A BLEED OF AIR FROM BEHIND THE COMPRESSOR AND SUPPLYING IT BEHIND THE TURBINE IN AN AIRCRAFT ENGINE

Zalety stosowania upustu części powietrza zza sprężarki i doprowadzania go z tyłu turbiny w turbinowym silniku lotniczym

Abstract: *The research paper discusses the advantages of using compressor downstream air partial bleed and supplying it downstream of the turbine, which was applied in a prototype of a "bypass" turbojet engine. The impact of such a solution on the value of achieved basic operating parameters of the engine was described, i.e., unit thrust and unit power consumption. The presented attempt to compare these parameters with the parameters achieved for a turbojet, single flow engine is very important; in the first case without air bleed, and in the second, with air bleed to the environment and with the parameters of a turbojet, turbofan engine with a jet mixer.*

Keywords: aviation engine operating parameters, jet engine designs, aviation engine air bleed

Streszczenie: *W artykule omówiono korzyści wynikające z częściowego upustu powietrza za sprężarką i dostarczania go za turbiną, co zostało zastosowane w prototypie turbinowego silnika odrzutowego typu „bypass". Opisano wpływ takiego rozwiązania na wartość uzyskiwanych podstawowych parametrów eksploatacyjnych silnika, tj. ciągu jednostkowego i jednostkowego zużycia paliwa. Istotna jest zaprezentowana próba porównania tych parametrów z parametrami uzyskiwanymi dla turbinowego silnika odrzutowego jednoprzepływowego; w pierwszym przypadku bez upustu powietrza, a w drugim z upustem, oraz z parametrami turbinowego silnika odrzutowego dwuprzepływowego z mieszalnikiem strumieni.*

Słowa kluczowe: parametry eksploatacyjne silnika lotniczego, konstrukcje silników odrzutowych, wpust powietrza silnika lotniczego

1. Introduction

The compressor air bleed is very common in modern turbojet engines [4, 5, 7]. Usually, the bled air is discharged to the environment (or the turbofan engine external duct). The aim of this bleeding is mainly counteracting unstable compressor operation. For these reasons, the bleeding is executed usually from the middle stages of the compressor.

In the 1970s, Pratt &Whitney developed a diagram of a twin-rotor turbojet engine, which used compressor air bleeding, supplying it downstream of the turbine (turbine bypass engine) [4, 6]. Up to 25% of the air stream flowing through the compressor is bled in the maximum operating range. With decreasing engine thrust, the flow rate of the flue gas stream flowing through the turbine is maintained, and the volume of air bled downstream of the compressor is decreased. This enables maintaining the rotational speed of the engine at a set level of 100%, within a sufficiently broad range of total and unit thrust changes. This leads to improving the dimensionless coefficient of aircraft aerodynamic force resultant c_R (even if only due to decreased pulsation of the stream flowing from the engine) and decreasing specific losses due to a better cooperation of the engine and the inlet. For various reasons however, this engine did not find widespread application in aviation and never took off.

The joint research of Pratt&Whitney and Boeing led, in turn, to designing a single-rotor engine utilizing this type of air bleeding. A diagram of such an engine is shown in fig. 1, which additionally shows the distribution of jet pressure flowing through the duct of such an engine, taking into account airspeed V.

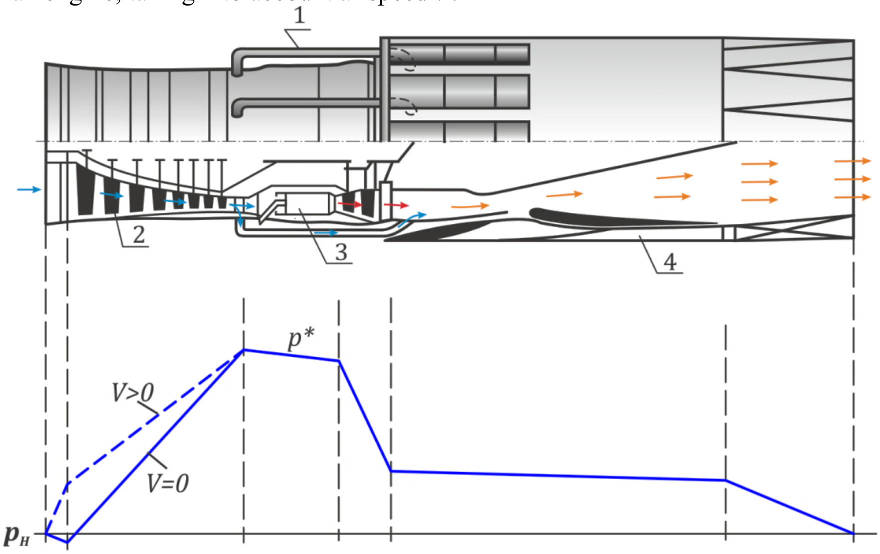

Fig. 1. Diagram of a “bypass” turbojet engine: 1 – flow duct for the air bled downstream of the compressor and supplied downstream of the turbine, 2 – adjustable compressor, 3 – combustion chamber with a low emission level for toxic flue gas components, 4 – exhaust nozzle with thrust reverses

The work cycle of this type of "bypass" engine is a typical cycle of a single-flow engine with a variable operating field depending on the amount of air released from behind the compressor and supplied to the turbine - an example in the pressure-volume (p-v) system is shown in fig. 2, and in the temperature - entropy (T-S) in fig. 3.

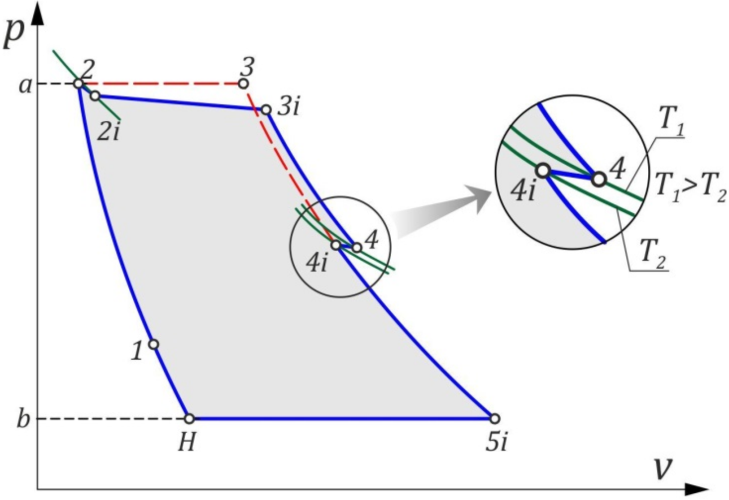

Fig. 2. The real work cycle of "bypass" engine type in the p-v system

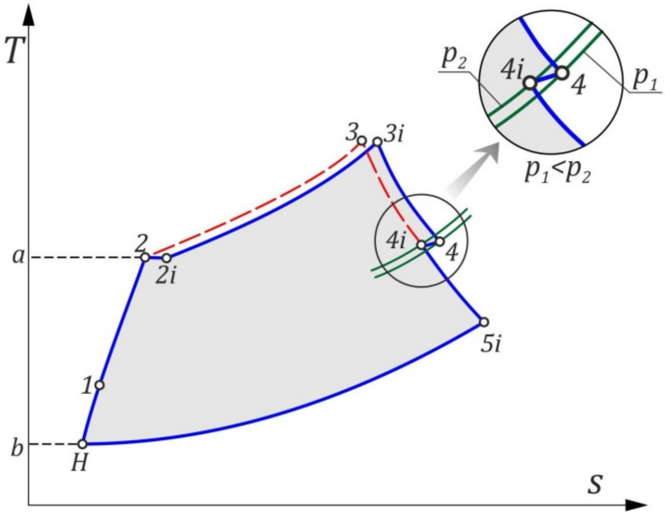

Fig. 3. The real work cycle of "bypass" engine type in the T-S system

The dependence of the work of the cycle for the "bypass" type engine is more convenient to present in the form showing the difference between the work of the air engine without the air bleeding and the work cycle of this engine, i.e. in the form:

$$l_{obi} = l_{ob} - \nu\varphi_D^2 c'_p T_H^* \left\{ \Delta^* - \frac{B\left[\left(1+\bar{l}_s\right)c_p - c'_p\eta_m\bar{l}_s\right]}{c'_p\eta_s^*\eta_m} - 1 \right\} \tag{1}$$

where: $\nu = \frac{\dot{m}_{up}}{\dot{m}}$ - the relative amount of air released from behind the compressor ($\dot{m}_{up}$ - part of the air released from behind the compressor behind the turbine),

φ_D - velocity loss factor in the exhaust nozzle (usually $\varphi_D = 0.97 \div 0.99$),

c_p, c'_p - the specific heat of air and flue gas, respectively,

T_H^* - total air temperature at the compressor inlet section,

η_m, η_s^* - respectively mechanical efficiency of the engine and compressor,

Δ^* - the degree of heating of the equivalent single flow engine,

$\bar{l}_s = \frac{L'_s}{L_s}$ - division of compressor operation with air release, according to [4] (L'_s - the part of the work compressor required to compress the bleed air, L_s - the work compressor),

$B = \pi_s^{*\frac{k-1}{k}} - 1$ - constant depending on the compressor value π_s^* (*k* – the isentrope exponent for air is equal 1,4).

2. Operating parameters of a “bypass” engine

A turbojet engine with compressor air bleed and its supply downstream of the turbine is a new solution, which is not yet operated on flying aircraft. The impact of this type of compressor air bleed on unit thrust, unit fuel consumption, the character of actual circulation and individual engine parameters requires conducting rather detailed analyses. In any event, partial air bleeding influences the changes of turbojet engine operating parameters – in particular, it causes a decrease of its thrust [1, 2, 3]. The objective of the “bypass” engine analysis is to determine the impact magnitude for this type of air bleeding on selected operating parameters of a turbojet engine.

The computational model for a turbojet engine using compressor downstream air bleeding and supplying downstream of the turbine is adopted as for a single-flow engine, taking into account the impact of bled air on the parameters of exhaust gas stream flowing to the exhaust nozzle. The temperature of bled compressor air has a value determined by a relationship:

$$T_{2i}^* = T_H^* \left(1 + \frac{\pi_{Si}^{*\frac{k-1}{k}} - 1}{\eta_S^*} \right) \tag{2}$$

where: $\pi_{Si}^* = \pi_S^{*\frac{i}{z}}$ - compressor compression ratio at the bleed point, assuming identical efficiency of all its stages $\left(\eta_{Si}^* = \eta_S^*\right)$,

T_H^* - air total temperature in the outlet cross-section of the compressor,

η_S^* - compressor efficiency - usually $\eta_S^* = 0.84 \div 0.88$ [1],

k - air isentrope exponent $(k = 1.4)$,

z - number of compressor stages;

i - number of compressor stage, with air exhaust behind it.

Whereas the impact pressure at the air bleed point is:

$$p_{2i}^* = p_1^* \cdot \pi_{Si}^* \tag{3}$$

where: p_1^* - impact pressure upstream of the compressor.

In the event of an inflow of bled air downstream of the turbine, the exhaust gas stream downstream of the turbine T_4^* changes, and its specific value can be determined deriving from the flow energy balance, i.e.:

$$c_{pm} T_{4i}^* \dot{m} = c_p T_{2i}^* \dot{m}_{up} + c_p^{'} T_4^* \left(\dot{m} - \dot{m}_{up} \right) \tag{4}$$

where: T_{4i}^* - impact temperature of the mixture of turbine downstream exhaust gases and the air bled from the compressor after mixing,

T_4^* - exhaust gas temperature downstream of the turbine, calculated from the comparison of the turbine available power and the power necessary for compressor drive,

$\dot{m}$ - air flow rate,

$\dot{m}_{up}$ - flow rate of the air section bled from the compressor and supplied downstream of the turbine,

$c_p, c_p^{'}$ - specific heat of air and exhaust gases, respectively,

c_{pm} - specific heat of the mixture of exhaust gases downstream of the turbine and the air bled from the compressor - can be calculated from a relationship:

$$c_{pm} = \nu \cdot c_p + (1-\nu) \cdot c_p^{'} ;$$

$\nu = \frac{\dot{m}_{up}}{\dot{m}}$ - relative volume of air bled from the compressor.

Hence, the impact temperature of the mixture of turbine downstream exhaust gases and the air bled from the compressor T_{4i}^* can be calculated from the relationship:

$$T_{4i}^* = \frac{\nu \cdot c_p \cdot T_{2i}^* + (1-\nu) \cdot c_p^{'} \cdot T_4^*}{c_{pm}} \tag{5}$$

Whereas the pressure of the exhaust gases-air mixture p_{4i}^* can be calculated from the relationship:

$$p_{4i}^* = \left[\nu \cdot p_{2i}^{*\frac{k-1}{k}} + (1-\nu) \cdot p_4^{*\frac{k'-1}{k'}} \right]^{\frac{k'}{k'-1}} \tag{6}$$

where: p_4^* - pressure downstream of the turbine, calculated from the comparison of the turbine available power and the power necessary for compressor drive,

k' - exhaust gas isentrope exponent $(k' = 1.33)$.

Unit thrust of a turbojet engine with the supply of air bled from the compressor downstream of the turbine (k_{ji}) and unit fuel consumption (c_{ji}), under the assumption of critical pressure ration in the exhaust nozzle are:

$$k_{ji} = \varphi_D \sqrt{2\frac{k'}{k'-1}R'T^*_{4i}} - V \tag{7}$$

$$c_{ji} = \frac{q_{KS}}{\xi_{KS} W_u k_{ji}} \tag{8}$$

where: φ_D - speed loss factor in the exhaust nozzle, usually 0.97÷0.99,

k' - exhaust gas isentrope exponent $(k' = 1.33)$,

R' - individual gas constant for exhaust gases,

V - airspeed,

q_{KS} - actual heat supplied in the combustion chamber to the air mass unit over a unit of time,

ξ_{KS} - heat emission coefficient in the combustion chamber,

W_u - fuel calorific value.

Air supply from the compressor downstream of the turbine causes certain changes of the achieved basic parameters of the engine. The magnitude of this impact is most conveniently determined by presenting a relative unit thrust of the engine and relative unit fuel consumption. Moreover, this impact depends on the type of the engine control system. For an engine, which is controlled by a constant heating degree criterion - $\Delta^* = const$ the value of absolute unit thrust of a “bypass” engine, relative to a unit thrust for an engine without the bleeding, can be determined from the relationship:

$$\bar{k}_{ji} = \frac{k_{ji}}{k_j} = \frac{\varphi_D \sqrt{2c'_p T^*_H \left\{ \Delta^* \left[1 - \nu - \frac{A}{\eta^*_S} \left(\frac{1 - \nu + \nu \bar{l}_S}{\eta_m} - \nu \bar{l}_S \right) \right] + \nu \right\}} - V}{\varphi_D \sqrt{2c'_p T^*_H \Delta^* \left(1 - \frac{A}{\eta^*_S \eta_m} \right)} - V} \tag{9}$$

where: φ_D - speed loss factor in the exhaust nozzle, usually 0.97÷0.99,

η_m - mechanical efficiency of a rotor assembly, usually 0.99÷0.995,

η^*_S - compressor efficiency, usually 0.84÷0.88,

$\overline{l}_S = \frac{l'_S}{l_S}$ - operational division of a compressor with air bleeding: l_S – compressor effective operation, l'_S – compressor effective operation transferred to the bled air stream,

$A = \eta_m \overset{*}{\eta}_S \overset{*}{\eta}_T C = const$, including $C = 1 - \frac{1}{\pi_T^{*\frac{k'-1}{k'}}} = const$ - assumptions.

Whereas, relative unit fuel consumption for a "bypass" engine, in relation to an engine without the bleeding can be determined from the relationship:

$$\overline{c}_j = \frac{\overline{q}_{KSi}}{\overline{k}_{ji}} \tag{10}$$

where: $\overline{q}_{KSi}$ - relative heat supplied to the combustion chamber, defined as a ratio between the heat supplied to a "bypass" engine combustion chamber and an engine without air bleeding.

Fig. 2a shows diagrams of engines: single flow without air bleeding and "bypass" single flow, which were used as a base for analysing the impact of air bleeding from the compressor downstream of the turbine on the unit thrust and unit fuel consumption.

Fig. 2b shows the dependency of the impact of air bleeding on the relative engine thrust from the exhaust gas temperature upstream of the turbine T_3^* and the compressor compression ratio π_S^*. Increasing exhaust gas temperature upstream of the turbine increases the decrease of the relative engine thrust, while the compressor compression ratio increase – decreases it. Fig. 2c shows the impact of the airspeed on the value of the relative engine thrust decrease (e.g. for *Ma*=2 at 25% air bleeding by approximately 4%).

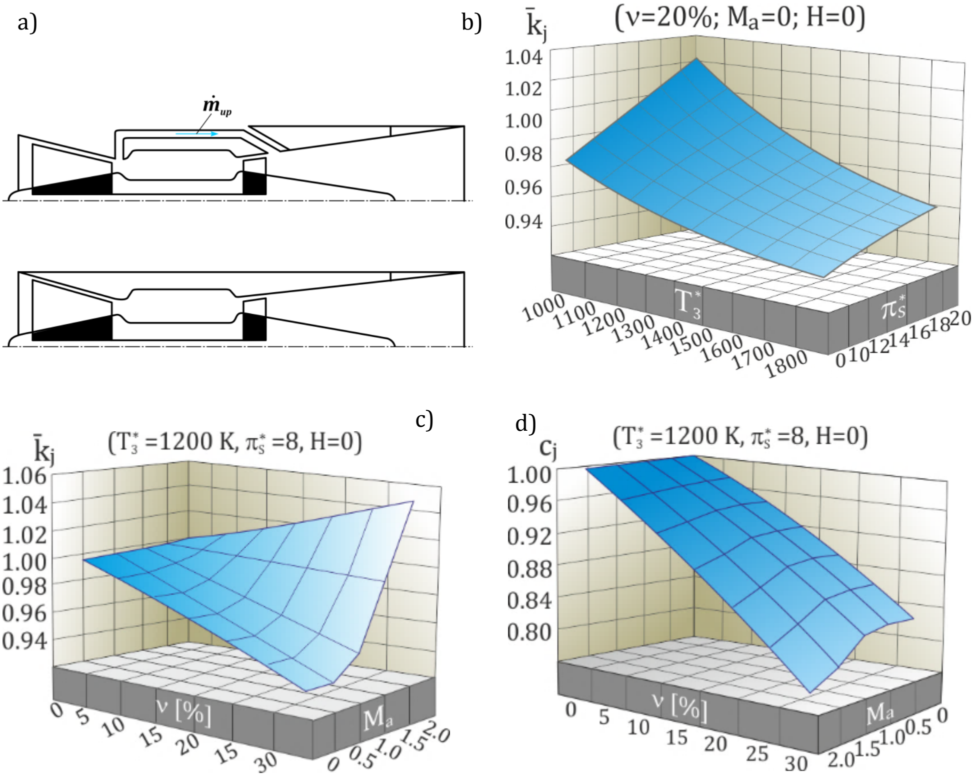

Fig. 4. Relative relationships of “bypass” engine operating parameters: a – diagrams of a “bypass” engine and a single flow without air bleeding; b – thrust on exhaust gas temperature upstream of the turbineT_3^* and compressor compression ratio π_S^*; c – thrust on air speed *Ma* and the volume of bled air ν; d – unit fuel consumption on air speed *Ma* and the volume of bled air ν

Nevertheless, the relative unit fuel consumption decreases with increasing volume of air supplied from downstream of the compressor downstream of the turbine. Fig. 2d shows the dependency of relative unit fuel consumption on the volume of bled air and air speed. Air speed increase increases the value of relative decrease of unit fuel consumption.

Therefore, it should be concluded that bleeding air downstream of the compressor and supplying downstream of the turbine results in a decrease of relative engine thrust (up to approx. 5%), which can be eliminated by increasing the compressor compression ratio and air speed. This provides significant decrease of the relative unit fuel consumption (up to approx. 15%), which can be further decreased by increasing air speed.

A comparison of the achieved unit thrust values for a turbojet engine with air bleeding to the environment k_{jup} and a „bypass” engine k_{ji} can be determined from the relationship:

$$\bar{k}_{ji} = \frac{k_{jup}}{k_{ji}} = \sqrt{1-\nu\left\{1-\nu\left[1-\frac{\dfrac{\eta_S^*}{\Delta^*}+\bar{l}_S A}{\eta_S^* - \dfrac{A}{\eta_m}\left(1+\dfrac{\nu\bar{l}_S}{1-\nu}\right)}\right]\right\}} \tag{11}$$

Analyses of the achieved unit thrust values in a turbojet engine with air bled to the environment and a “bypass” engine indicate that a “bypass” engine is much more advantageous in terms of the values of achieved thrust (by over 25% for a 25% air discharge). This value can be increased by increasing the compressor compression ratio (fig. 3b) and increasing the air speed (fig. 3c).

The analysis of unit fuel consumption should be conducted using the relationship (9), under the assumption $\overline{q}_{KS} = 1$, which indicates that these are similar engines but with different methods for partial air discharge. The conducted analysis of unit fuel consumption for both engines, calculated on the basis of the relationship (9) shows that together with increasing volume of bled air, as well as increasing air speed, a “bypass” engine is becoming significantly more cost-efficient (fig. 3d).

It means that the “bypass” engine enables increased engine thrust in relation to an engine with air bleeding to the environment by over 25%, at the same time improving its cost-efficiency by over 20% in ground conditions. The aforementioned differences are increased in favour of a “bypass” engine is as a result of increasing compressor compression ratio and air speed.

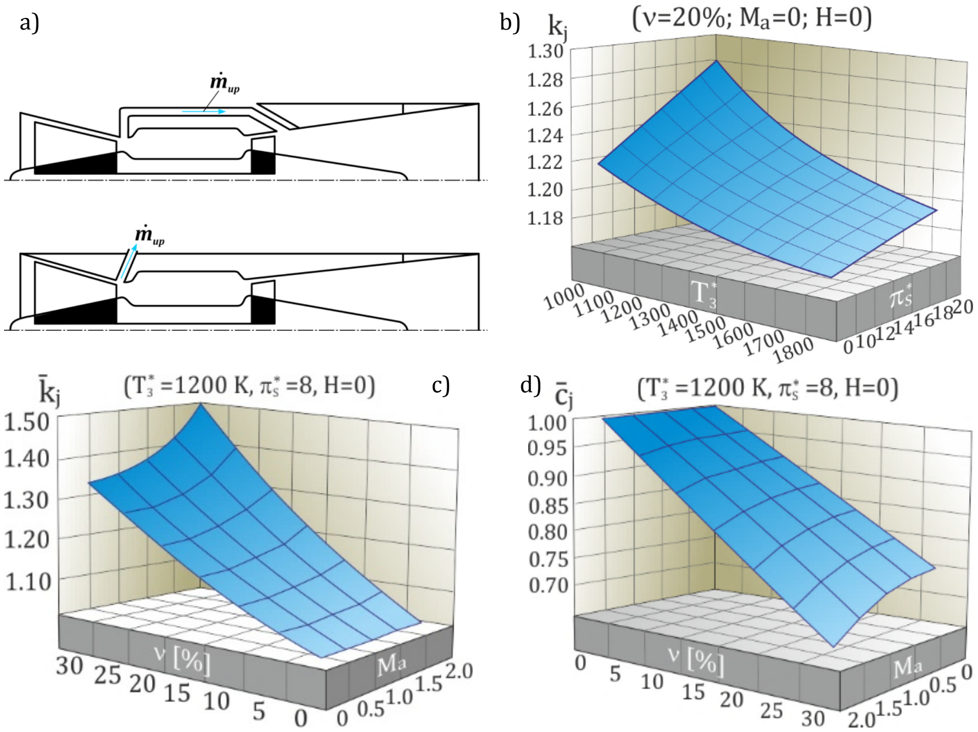

Fig. 5. Dependency of operating parameters of a "bypass" engine and an engine with bleeding into the atmosphere: a – diagrams of a "bypass" engine and a single flow without air bleeding; b – thrust on exhaust gas temperature upstream of the turbine $\boldsymbol{T_3^*}$ and compressor compression ratio $\boldsymbol{\pi_S^*}$; c – thrust on air speed *Ma* and the volume of bled air ν; d – unit fuel consumption on air speed *Ma* and the volume of bled air ν

The comparison of the operating parameters of a bypass engine and a turbo-fan engine with a mixer (with air flow rate in the external duct similar to the air bled downstream of the turbine in a bypass engine) is achieved by specifying the combustion chamber heat balance, in the form:

$$\dot{m}_I c_p T_2^* + \xi_{KS} W_u C_S = \dot{m}_I c_p' T_3^* \tag{12}$$

For the previously adopted control system according to a constant heating degree criterion - $\Delta^* = const$, this enables to determine the relationship for comparing the amount of heat supplied to the combustion chambers of both engines, in the form:

$$\overline{q}_{KS}=\frac{q_{KSm}}{q_{KSi}}=\frac{\Delta^{*}\left(1-A\right)-1+\dfrac{\nu D\eta_{S}^{*}}{\left(1-\nu\right)\eta_{W}^{*}}}{\Delta^{*}\left[1-\dfrac{\left(1-\nu\right)A}{1-\nu\left(1-\overline{l}_{S}\right)}\right]-1} \tag{13}$$

Whereas when considering the issue for engines operating on the ground (*V=0*), the relation of unit thrusts for a turbo-fan engine with a mixer and an engine with air supply downstream of the turbine - for the constant heating degree criterion $\left(\Delta^{*}=const\right)$ – is determined from the relationship:

$$\overline{k}_{j}=\frac{k_{jm}}{k_{ji}}=\sqrt{\frac{\left(1-\nu\right)\Delta^{*}\left(1-\dfrac{A}{\eta_{S}^{*}\eta_{m}}\right)+\nu D\left(1-\dfrac{\eta_{S}^{*}}{\eta_{W}^{*}\eta_{m}}\right)+\nu}{\Delta^{*}\left\{1-\nu-\dfrac{A}{\eta_{S}^{*}}\left[\dfrac{1-\nu\left(1-\overline{l}_{S}\right)}{\eta_{m}}-\nu\overline{l}_{S}\right]\right\}+\nu}} \tag{14}$$

A comparison between these engines shows a minor difference in the values of achieved thrusts, in favour of the “bypass” engine (by almost 5% for a 25% air bleed). This difference grows as a result of increasing compressor compression ratio π_S^*, whereas it decreases – as a result of increasing temperature of exhaust gases upstream of the turbine T_3^* (fig. 4b). Fig. 4c shows the analysis of this comparison, in relation to the volume of bled air and air speed. Increasing air speed increases the difference in the value of achieved thrust, in favour of a “bypass” engine. Dependency of unit fuel consumption for both engines on the volume of bled air and air speed is shown in fig. 4d. A “bypass” engine is becoming slightly more cost-efficient than a turbofan engine with a mixer both with increasing volume of bled air, as well as the air speed.

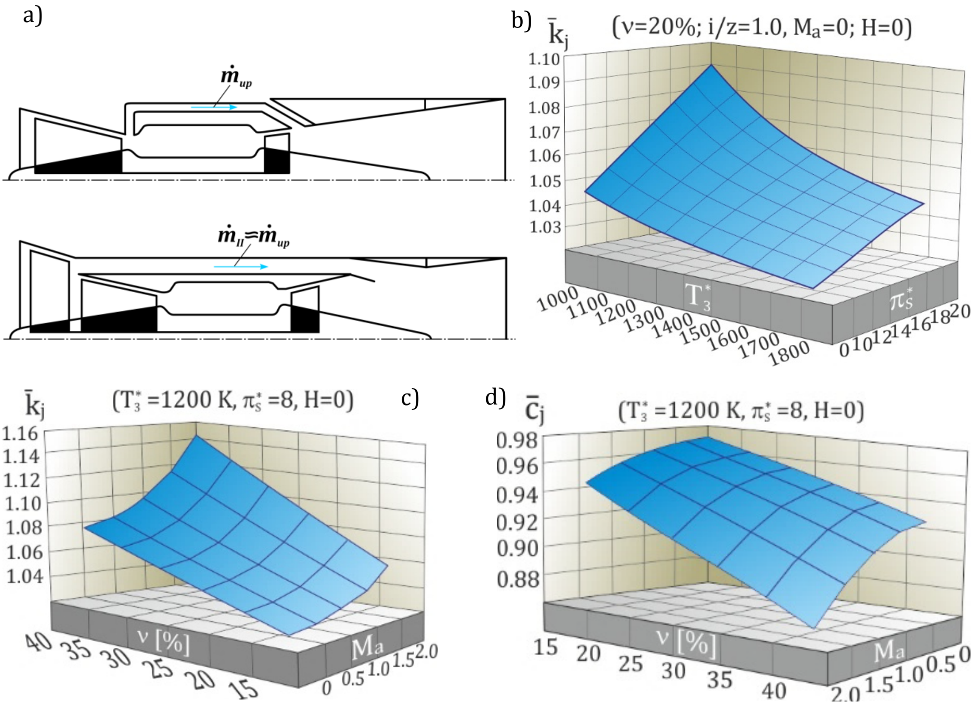

Fig. 6. Relation between operating parameters of a "bypass" engine and operating parameters of a turbofan engine with a mixer: a – diagrams of a "bypass" engine and a turbofan with a mixer; b – thrust on exhaust gas temperature upstream of the turbine $\boldsymbol{T_3^*}$ and compressor compression ratio $\boldsymbol{\pi_S^*}$; c – thrust on air speed *Ma* and the volume of bled air ν; d – unit fuel consumption on air speed *Ma* and the volume of bled air ν

Therefore, it can be concluded that a very minor increase of thrust (ca. 5%) and improved engine cost-efficiency (almost 5%) is achieved in a "bypass" engine, compared to these parameters for a turbo fan engine with a mixer. These advantageous differences may be even increased through increasing the compressor compression ratio and the flight air speed.

Simplifying, air from the compressor downstream of the turbine results in the relative engine thrust decreased by about 5% at a 25% volume of bled air. In engines with high compressor compression ratio (over 20) and during flight with high air speed – mainly supersonic – at low altitudes, there is a chance to eliminate this loss. On the other hand, the relative unit fuel consumption benefits, decreasing with increasing volume of bled air (by ca. 15% for a 25% discharge). This value can be increased further by increasing the airspeed.

3. Conclusions

Due to the value of the achieved thrust, as well as the unit fuel consumption, a “bypass” turbojet engine is much more efficient compared to the engine, where the air is bled outside of the engine. Also, in terms of the parameters, it is slightly better than a turbofan engine with a mixer, with similar air volumes flowing through external ducts. Hence, these engines can become competitors for turbofan engines, which is why, they can be placed at the same level as future generations of VCE (variable cycle engine) or VSCE (variable stream cycle engine) engines. Not negligible is the possibility to decrease the exhaust gas temperature of a “bypass” engine in combat aircraft propulsions, which decreases the probability of being hit with a homing missile using IR guidance

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