ADAPTIVE JET ENGINES, ADVANTAGES AND APPLICATION OPPORTUNITIES

Mirosław Kowalski

Air Force Institute of Technology
6 Księcia Bolesława Street, 01-494 Warsaw, Poland
tel.: +48 22 6851101, fax: +48 22 8364471
e-mail: miroslaw.kowalski@itwl.pl

Abstract

The paper has been intended to shortly describe the design of an adaptive jet engine, commonly termed 'the bypass engine'. Examples have been presented of how the bleeding of air affects the most essential engine performance characteristics, i.e. thrust, specific fuel consumption, and efficiency. Pointed out are economic advantages (only slight) of the application of this design as compared to the one-pass turbojet engine with no bleed. Furthermore, considered are capabilities to adapt an engine design of the bypass type for a one-pass turbojet engine K-15 as one of several upgrade opportunities. Simulation-based computations have proved, however, that there are some limitations on the bleed air amount and initial engine operational range for the accomplishment of the idea from the standpoint of capabilities to maintain conditions for the compressor-turbine matching. Also, the effect of this type of air bleeding upon the engine running-up process and the change in the running-up time for this type of the upgraded engine has been shown. In the Recapitulation and Conclusions section a mention has been made on the amount of bleed air to be passed through external channels from behind the compressor to behind the turbine: the bleed air amount increases as the total rate of the air flow along the engine flow path increases. It means that better effects of applying this type of air bleeding processes are gained in large engines. Presented are also capabilities of further developments and applications.

Keywords: *transport, combustion engine, adaptation engine, parameters of the engine air*

1. Introduction

Widespread use of turbojet engines leads to more and new directions for their further development.

One of the more original, classified as a group of adaptive engines includes also a two-rotor engine designed by Pratt & Whitney, where a portion of air is bled from downstream of the compressor and then supplied to the area downstream the turbine when the engine is operated with the maximum performance (turbine bypass engine). For the maximum performance of the engine it is possible to bleed up to 25% of the air stream that passes through the compressor. The more the flow is throttled, the less percentage ratio of the air is bled from behind the compressor in order to maintain the compressor-turbine matching. It makes possible to keep the engine rpm of the engine at the predefined level of 100% within the sufficiently wide variation range of both the total and unit thrust.

Common research studies carried out by Boeing and Pratt & Whitney have led to the design of a single-spool engine with application of the bleed as described above (Fig. 1).

A peculiar feature of such a solution is implementation of external (with circular cross-section) bypass channels as well as a system that is capable to control air bleeding depending on the aircraft speed. Such a solution enables to improve efficiency of the engine, decrease its noise emission and emission of toxic compounds in exhaust gas. The additional advantage of the presented solution is the relatively lowly sophisticated standard solution and possibility to apply the solution to engines that already have been in use.

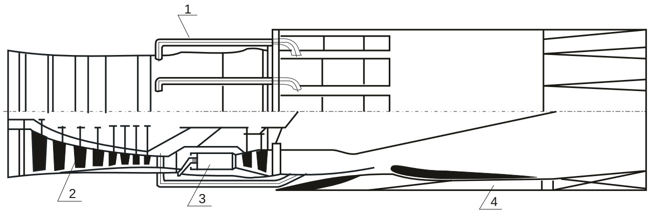

Fig.1. Cross-section diagram of the turbine jet engine of 'bypass' type: 1 – bypass channel of air delivered from downstream of the compressor to the area downstream the turbine, 2 - controllable and adjustable compressor, 3 – combustion channel with low-emission of toxic components in exhaust gas, 4 – outlet jet with thrust reverser

2. Air bleeding and performance parameters of engines

Basic performance parameters of aircraft engines include among others unit thrust and unit consumption of fuel. In order to analyze, how air bleeding carried out in adaptive turbojet engines affects these performance parameters it is necessary to start from the energy balance of flow, i.e.:

$$\dot{m}_I L_T \eta_m = \dot{m}_I L_S + \dot{m}_{II} L'_S, \tag{1}$$

where: L_S, L_T - respective values of work performed by the compressor and the turbine,
L'_S - a portion of the compressor work that must be used for recompression of air that is bled to the external channel

Also, the thermal balance for the combustion chamber can be expressed by the formula below:

$$\dot{m}_I c_p T_2^* + \xi_{KS} W_u C_S = \dot{m}_I c'_p T_3^*, \tag{2}$$

where: c_p, c'_p - respective values of specific heat for air and combustion gas,
ξ_{KS} - coefficient of heat emission inside the combustion chamber,
W_u - calorific value of fuel for avionic engines (kerosene),
C_S - amount of fuel supplied to the combustion chamber during 1 second.

Starting from the foregoing relationships and using appropriate assumptions and simplifications, e.g. having assumed the critical pressure ratio in the output jet and having applied the control principle according to the criterion of the constant heating degree of the stream (Δ^*=const), it is possible to derive the following formula for calculation of the unit thrust to be achieved by adaptive engines:

$$k_{jm} = \varphi_D \sqrt{\frac{2c'_p T_H^* \left\{ \Delta^* \left[1 - A \left(\frac{1 + \bar{m}\bar{l}_S}{\eta_s^* \eta_T^* \eta_m} - \bar{m} \right) \right] + \bar{m} \right\}}{1 + \bar{m}}}, \tag{3}$$

where: φ_D - coefficient of velocity loss inside the output jet (φ_D =0.97-0.99);

as well as for calculation of the unit fuel consumption:

$$\bar{c}_{jm} = \frac{q_{KSm}}{\xi_{KS} W_u k_{jm}}, \tag{4}$$

where: q_{KSm} – amount of heat supplied to the combustion chamber, determined by means of the relationship:

$$q_{KSm} = T_H^* \left[\Delta^* \left(1 - \frac{A}{1 + \bar{m}\bar{l}_S} \right) - 1 \right]. \tag{5}$$

Graphic diagrams for the unit thrust and unit fuel consumption that have been plotted on the basis of the foregoing relationships are presented in Fig. 2 (the obtained values are referred to respective graphs obtained for equivalent single-flow engine without air bleeding). One can see that application of such bleedings leads to decrease of both the unit thrust and the unit fuel consumption. Nevertheless, drop of the unit fuel consumption is more significant, which is the benefit from application of such air bleeding technique. Eventually, a number of benefits can be achieved, including growth of general performance achieved by that engine, which is shown in Fig. 3.

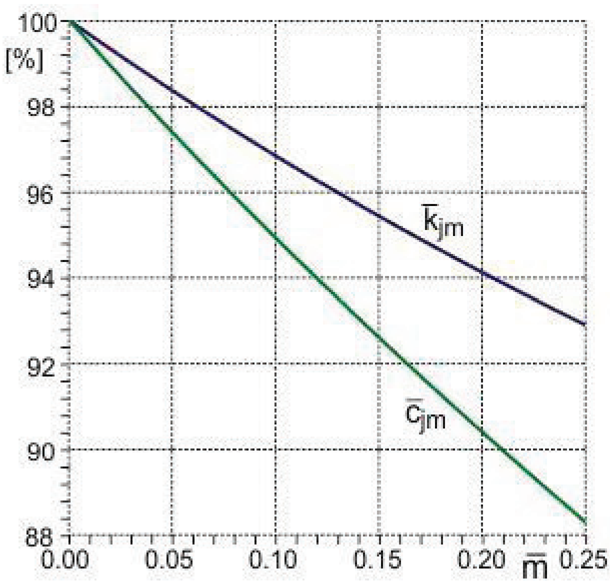

Fig. 2. Relative decrease of the unit thrust and the unit fuel consumption demonstrated by an adaptive engine

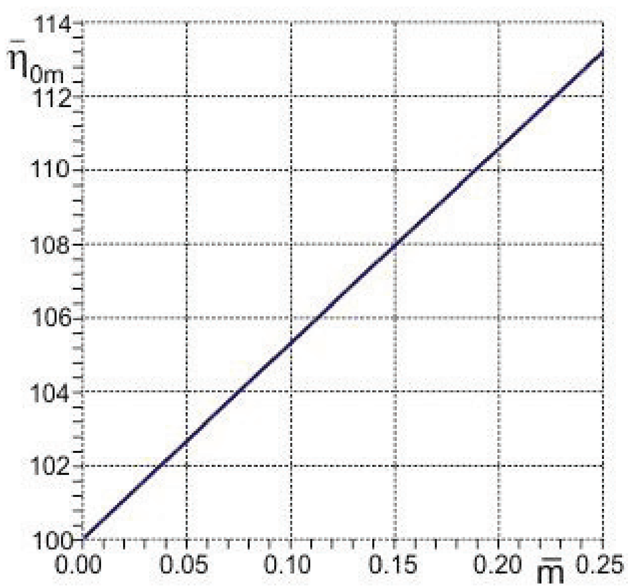

Fig. 3. Relative general efficiency of an adaptive engine

On the other hand, for motor of the 'bypass' type, it is possible to start from the relationship that describes energy balance of flow in the following form:

$$\dot{m}_{up} L'_S + (\dot{m} - \dot{m}_{up}) L_S = (\dot{m} - \dot{m}_{up}) L_T \eta_m \tag{6}$$

as well as from the thermal balance for the combustion chamber:

$$(\dot{m} - \dot{m}_{up}) c_p T_2^* + \xi_{KS} W_u C_S = (\dot{m} - \dot{m}_{up}) c'_p T_3^* . \tag{7}$$

After proper calculations and transformations it is possible to find out the relationship that describes amount of heat delivered to the combustion chamber:

$$q_{KSi} = (1-\nu)\bar{c}_p T_H^* \left[\Delta^* \left(1 - \frac{A}{1 + \frac{\nu \bar{l}_s}{1-\nu}} \right) - 1 \right] \tag{8}$$

and then the formula for the unit thrust k_{ji} of the engine:

$$k_{ji} = \varphi_D \sqrt{2c'_p T_H^* \left\{ \Delta^* \left[1 - \nu - \frac{A}{\eta_s^*} \left(\frac{1 - \nu + \nu \bar{l}_s}{\eta_m} - \nu \bar{l}_s \right) \right] + \nu \right\}} - V. \tag{9}$$

Use of the foregoing relationships and the formula (29) one can plot graphs for variations of the unit thrust and unit consumption of fuel (Fig. 4). The graphs demonstrate gradual decease of the both parameters, i.e. both the unit thrust and unit consumption of fuel in pace with increase of air amount that is bled from the engine. However, (similarly to the adaptive engines already analyzed in foregoing paragraphs), reduction rate of the unit fuel consumption is much steeper (by more than 2%), which confirms cost-effectiveness of these engines, chiefly due to the improvement of their general efficiency (Fig. 5).

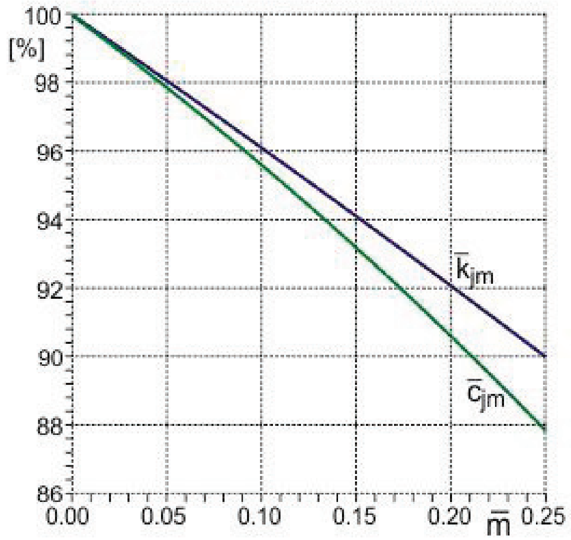

Fig. 4. Graph for the unit thrust and unit fuel consumption for a 'bypass' engine

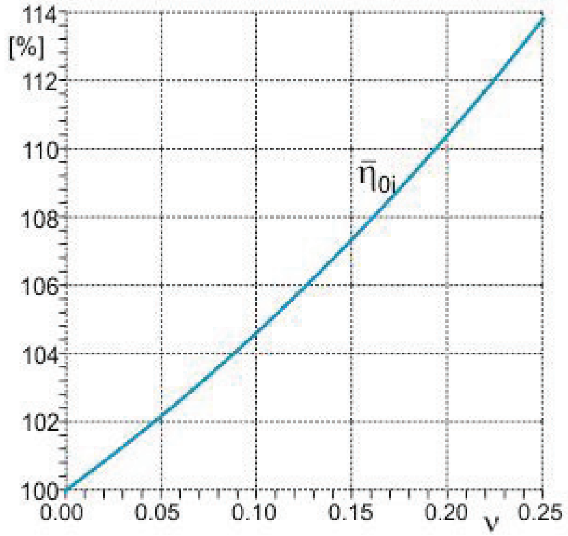

Fig. 5. Graph for the general efficiency for a 'bypass' engine

3. Possible implementation of air bleeding performed by 'bypass' engines to the k-15 motor

The design solution that consists in bleeding of air and is implemented to 'bypass' engines suggest the opportunity to apply one of the innovative techniques to existing engines, for instance K-15. Unfortunately, already completed simulative computations have demonstrated that there are some constrains to implementation of such solutions, in terms of both size and initial operation range due to the need to maintain correct collaboration between the turbine and the compressor. Fig. 6 presents typical graphic interpretation for acceleration of the K-15 engine, where the graph was obtained with use of the simulation model described in [2].

On the other hand, Fig. 7 shows how implementation of the aforementioned bleeding solution affects variations of the acceleration performance of the engine.

The presented results were obtained for 10% of air amount that was bled over the maximum steady operation range (i.e. 94.5% n_{max}). It was revealed that such air pleading leads to lowering of the collaboration line between the turbine and the compressor, with simultaneous increase of the reserve for stability. It leads to drop of power that is transferred from the turbine to the compressor and finally results in reduction of the compression factor that can be achieved by the compressor.

The similar effect was also achieved, when the already recommended amount of air bleeding was kept with simultaneous decrease of the operation range of the engine when the bleeding valve is opened. Fig. 9 presents conditions for breaching the collaboration conditions for 10% amount of air bleeding and opening of the bleeding valve at the operation range below 90%.

The reason for breaching of collaboration is drop of power that can be achieved by the turbine, which becomes insufficient to drive the compressor, auxiliary systems and overcome the mechanical resistance. Finally, it leads to breaching of collaboration conditions and eventual engine kills. Quality of the engine acceleration process can be assessed qualitatively by means of such a parameter as duration of the acceleration process. The effect of aforementioned air bleeding technique onto the values of achievable relative acceleration time is presented in Fig. 10.

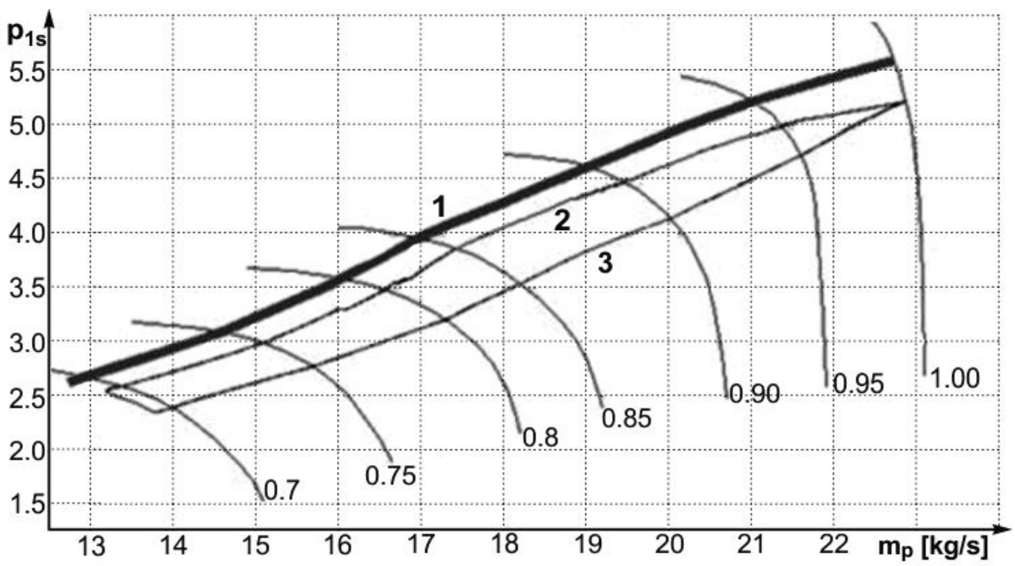

Fig. 6. Graphic interpretation for acceleration of the K-15 engine (without air bleeding) 1 – boundary line of steady operations, 2 – acceleration, 3 – line of collaboration under steady conditions.

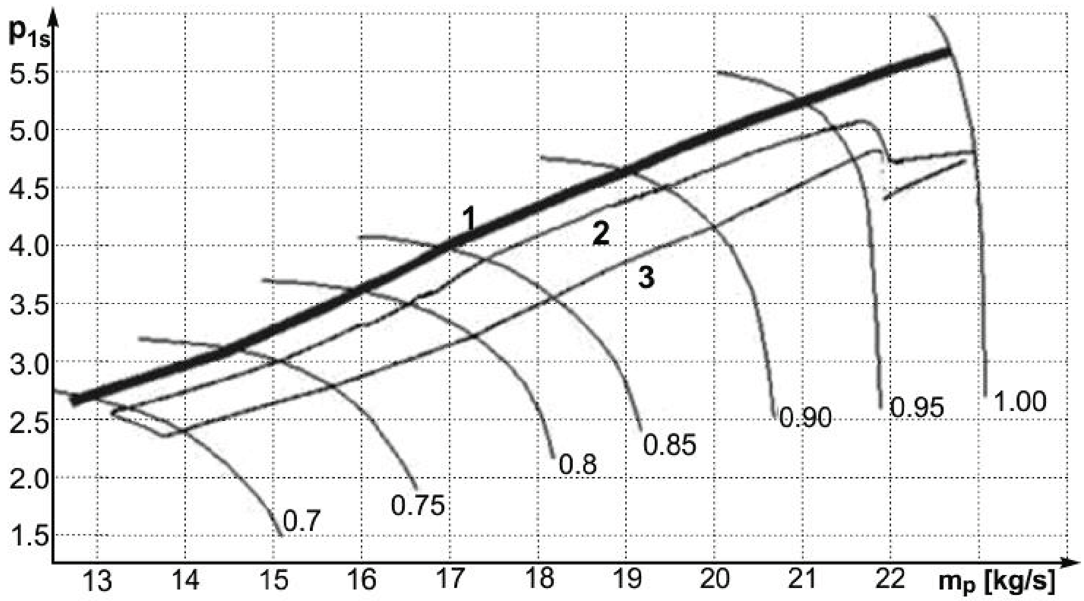

Fig. 7. Graphic interpretation for acceleration of the K-15 engine when 10% of air bleeding is applied to the maximum range of steady operation (ca. 94.5% n_{max})

Due to characteristic parameters attributable to individual subassemblies of the engine, the acceleration time was measured for rpm amounting to ca. 66% n_{max} (i.e. about 10500 rpm.). At the same time it is the rpm range that is actually used to measure acceleration time of the K-1 engine under conditions of regular operation. According to the engineering documentation the acceleration time of the engine measured from 66% to 95% of n_{max} should never exceed 4 seconds.

Anyway, due to the possibility to determine actual effect of air bleeding via the bypass channel onto the acceleration time, the simulative computations were restricted to the range from 66% to 99.5%, as the bleeding that is carried out for the maximum steady operation range ($n \approx 94.5\%$ n_{max}) has no practical effect onto that time. Actual effect is visible as late as for the range above 95% of n_{max}, which is the range that never occurs during regular operation of the engine. In addition the acceleration time was determined for amounts of air bleeding within the range from 0% to 15% of the overall air amount that passes the compressor through as any higher values breached collaborations conditions between the turbine and the compressor and made infeasible to measure the acceleration time.

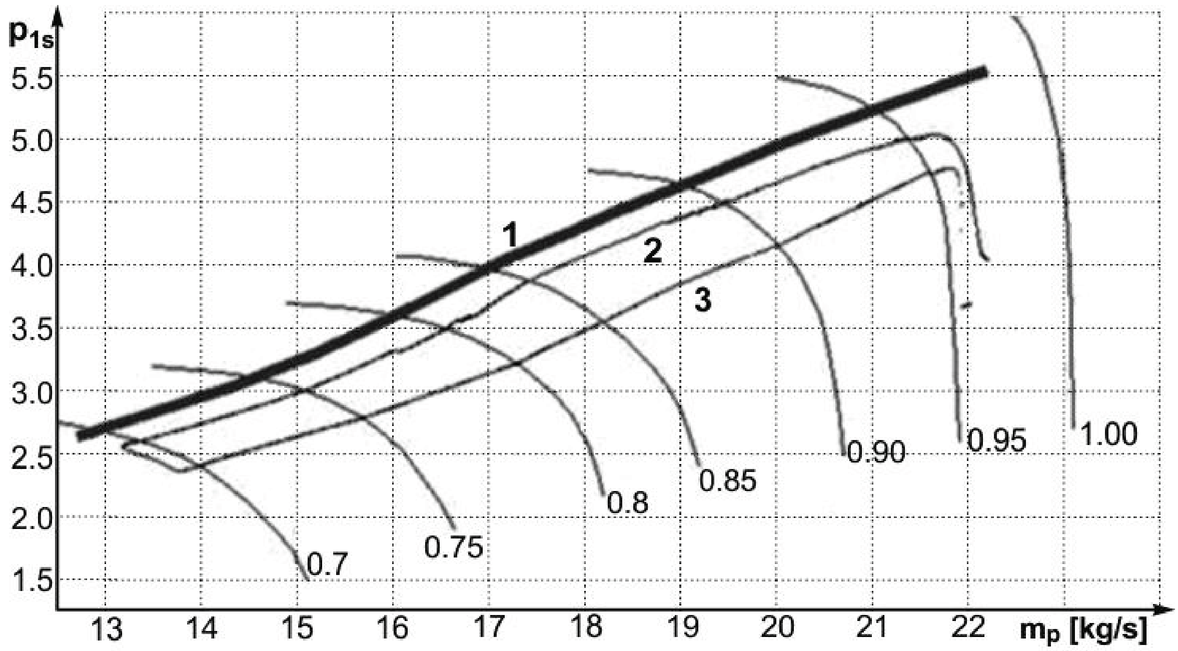

Fig. 8. Graphic interpretation for acceleration of the K-15 engine when 20% of air bleeding is applied to the maximum range of steady operation (i.e. ca. 94.5% of n_{max})

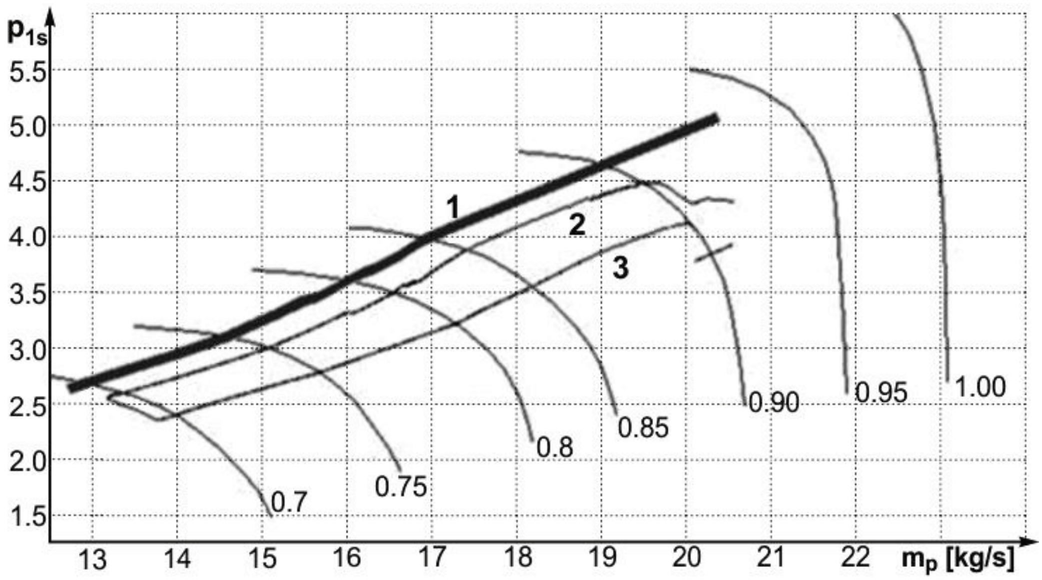

Fig. 9. Graphic interpretation for acceleration of the K-15 engine when 10% of air bleeding is applied to the range of ca. 88% n_{max}.

Analysis of Fig. 22 shows that the acceleration time increases in pace with growth of air amount to be bled. The increase is slightly more considerable for the range below 5% of the air bleeding (it reaches nearly 2%).

Finally, no findings were made that the acceleration time would substantially grow as a result of air bleeding implemented in the foregoing manner. Consequently, application of air bleeding to no extend prevents the engine from reaching the maximum operation range.

4. Recapitulation and conclusions

Operation of a turbojet engine of the bypass type is an issue of great interest on the one hand, on the other hand, however, the design itself may deliver lots of problems of constructional and product engineering nature, not mentioning the operational and maintenance ones.

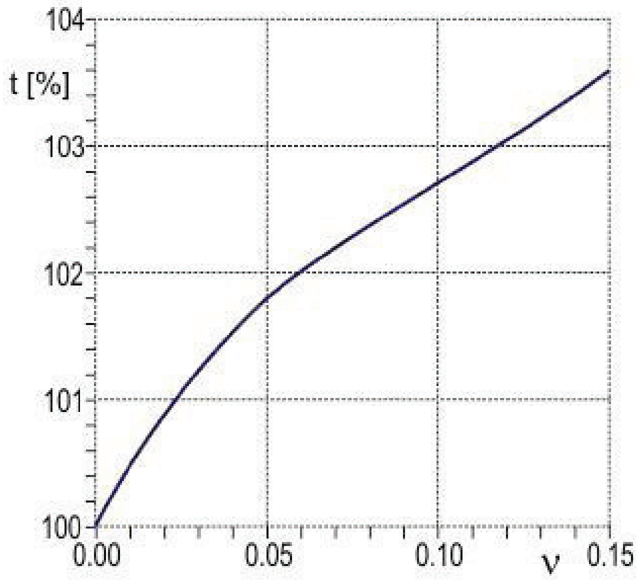

Fig. 10. Variation of the relative acceleration time as a function of relative air amount to be bled from downstream of the compressor to the downstream of the turbine

The design allows, however, of some economic profits and improvement in the overall efficiency of the engine. Furthermore, the bypass -engine design itself is such that offers an extra capability to apply it as a component to upgrade engines already in service, which pose problems with economical and efficient use thereof. This has been proved in the course of simulation-based tests of the K-15 engine operated with an additional module intended to take account of the bleed air passed through external channels for ranges close to maximum. Unfortunately, there are some (above-mentioned) limitations to be studied later on from the standpoint of conditions that may distort the compressor-turbine matching. It should be mentioned, however, that the amount of air that could be bled via external channels from behind the compressor to behind the turbine increases as the total rate of the air flow along the engine flow path increases. It means that better effects of applying this type of air bleeding processes are gained in large engines. Therefore, they are intended to provide propulsion for supersonic passenger and transport airplanes. Efforts are made to apply them as propulsion systems for supersonic strategic bombers, and fighter-bombers. Appearing are also ideas of applying the principle of operation of an adaptive and a ramjet engine to provide propulsion for a hypersonic aircraft flying at Ma > 4.

It has also been proved that the air-bleed process slightly increases the engine running-up time (by approximately 2%). It should be emphasized that such engines, due to improvement in economic efficiency, allow of range and endurance extension. And last but not least, the construction of such an engine seems to be much cheaper than that of a turbofan, with effects remaining comparable – see [2], [4].

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