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Wind-tunnel investigation of a twin-engine medium transport model equipped with an external blown flap

Petrov A.V. and Pigusov E.A.**
**Central Aerohydrodynamic Institute, 1 Zhukovsky St., Zhukovsky, Moscow Region, 140180, Russia*
albert.petrov@tsagi.ru evgeniy.pigusov@tsagi.ru

Abstract

The results of wind-tunnel investigation of twin-engine medium short takeoff and landing transport (MSTOL) model with the external blown flap (EBF) by exhaust flows of turbofan simulators are presented. The main features of exhaust blowing influence on aerodynamic characteristics of the model in takeoff, landing and cruising configurations are considered. The obtained values of lift coefficient of twin-engine model are close to according values of four-engine model. Thereby the experimental studies have shown the possibility of using the EBF to achieve the increased lift, required to provide the short takeoff and landing (STOL) capability for twin-engine transport aircraft.

1. Introduction

One of the most important requirements for transport aircraft is to provide STOL capability, including operation from unpaved runways. To solve this complicated problem, powered lift system (PLS) are usually used. These systems are based on the use of blowing wing by exhaust flow of turbofans (EBF) or slipstream of high-loading coaxial propfans for providing significant lift increment at takeoff and landing modes [1]. The application PLS on transport aircraft can increase the maximum lift coefficient of the airplane in 2÷2.5 times or more as compared to conventional high-lift devices, and accordingly provide to operate from short airfields. The transport aircraft efficiency is simultaneously increased by payload growth, expanding the possibilities of using the airfields with runway (RW) lengths from 600 to 800 m and reducing the cargo shipping time. The especial practical interest is of the EBF application on subsonic transport aircraft, thus they do not require radical changes of typical aerodynamic layout with placed engines on pylon under the wing. The increase in lift when the lower surface of wing and flaps blown by turbofan exhaust flows occurs due to deflection of the engine jets by flaps operating as jet deflectors and improvement of the flow around the flaps due to the high-pressure jet flow passing through the flap slots and the creation of additional aerodynamic load over the wing and flaps caused by the supercirculation effect [2].

The experimental investigations carried out at TsAGI have shown that application of the EBF on multi-engine airplanes allows to be significantly increased in lift during takeoff/landing regimes and provides the possibility of their landing on short RWs [3]. Currently, the most passenger and transport aircraft are usually equipped with twin-engine propulsion system due to the appearance of modern powerful and economical aircraft engines. Thereby, it is complicated to solve the problem of ensuring STOL capability of these aircraft with PLS.

This paper is aimed to estimate the effectiveness of the EBF application with two ultra-high bypass (UHBR) engines (BPR=16-18) for lift increasing at takeoff and landing operations of the MSTOL model. The selected configuration of the MSTOL and its parameters correspond to the typical aerodynamic configuration of with 25° swept high-wing, the T-shaped tail and with two UHBR turbofans mounted on pylons under the wing, designed to carry loads of up to 20 tons at a speed of 750-800 km/h at a distance of up to 2000 km [4]. The MSTOL is designed for operation from short paved or unpaved RWs with a length of no more than 800-1000 m. The test results of the MSTOL model with ground effect and in case of one engine inoperative are given in [5].

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2. MSTOL model and test condition

2.1 MSTOL model

Investigations of the EBF effectiveness on the MSTOL model with ejector simulators of UHBR engines (BPR=16 – 18) were carried out in the T-102 TsAGI low speed WT. T-102 is continuous-operation, closed layout WT with two reverse channels and an open test section designed to investigate aerodynamic characteristics of aircraft models at take-off, landing and low-speed flight. Two fans, each driven by a 250 kW electric motor, generate the flow. WT flow velocity is varied from 10 to 50 m/s. Elliptical test section is characterized by 4 m x 4 m x 2.33 m size. Models with wing area up to 0.8 m^2, wing span up to 2.5 m, and length up to 2.5 m are tested in the wind tunnel [6].

The aerodynamic model is a 1:20 scale model of the prototype of the MSTOL. Three-view drawing of the MSTOL model is shown in Figure 1. A basic model was manufactured as a version of a four-engine airplane, which was then modified to a two-engine version by removing the outboard engines. The main results of the testing of the four-engine airplane are presented in [1], [3]. Dimensional data of the model are given in Table 1.

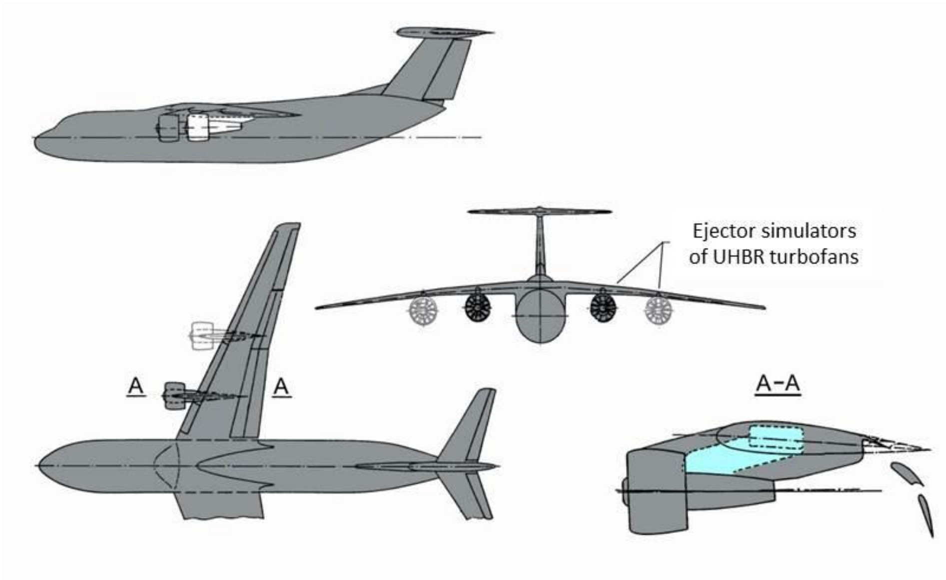

Figure 1: Three-view drawing of the MSTOL model

Table 1: Dimensional data of the MSTOL model

Wing area	0.742 m^2
Mean aerodynamic chord (MAC)	0.32 m
Wingspan	2.51 m
Sweepback angle	25°
Aspect ratio	8.5
Taper ratio	3
Fuselage length	2.3 m
Fuselage diameter	0.26 m
Wing incidence angle	+4°

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The wing high-lift devices consist of double-slotted flaps with the spoiler droop (SD) and slats. The wing trailing edge with retracted flap position is shown in Figure 2a. Flaps with the relative span of 73% and the chord of 32% were tested in two positions: flaps deflected by δ_f=30°/0, corresponding to the takeoff condition (See Figure 2b); flaps deflected by δ_f=40°/30°, corresponding to the landing condition (See Figure 2c). The relative height flap slots are equal to 2.5% of chord. The SD deflects down up to 12º. The slat is the 15% of the wing chord and is extended from the fuselage to the wingtip. The slats were deflected by 20° and 40°, corresponding to the takeoff and the landing conditions.

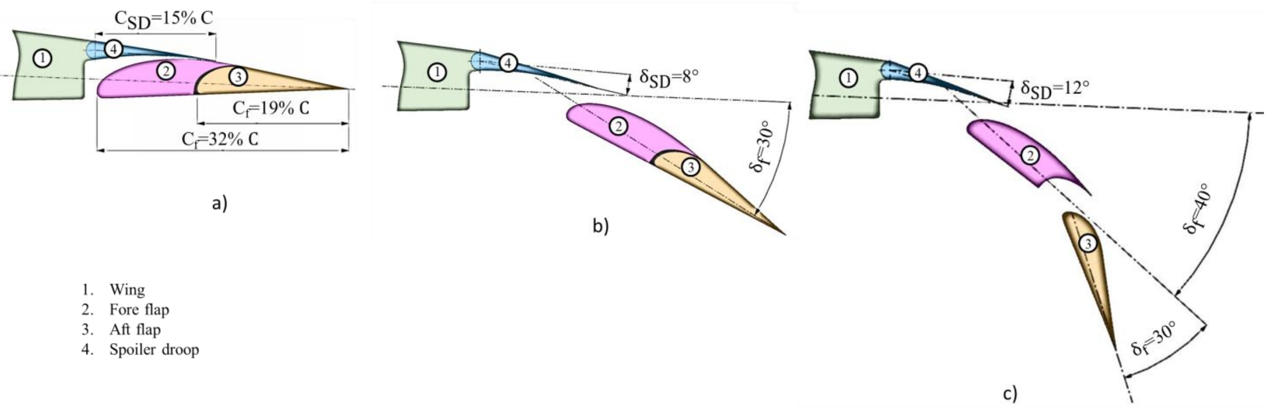

Figure 2: The high-lift devices of the wing trailing edge

The model was equipped with two UHBR turbofan ejector simulators. The ejector simulator, imitating a fan and gas generator, was used to provide the engine thrust coefficient. Compressed cold air (up to 500 kPa) was brought to a plenum chamber in the wing through an air duct strut. The ejectors were located at 28.33% of half span. The operation of the simulators was controlled by changing the air pressure in the external receiver with pressure control in the air duct strut.

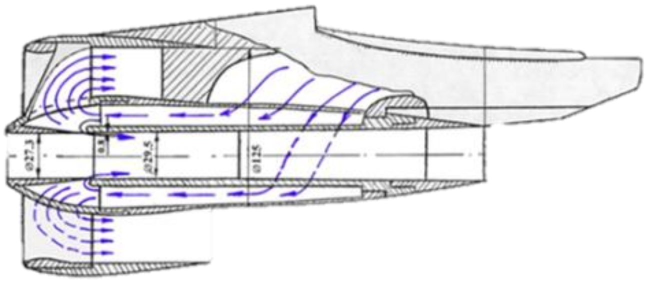

Figure 3: Sketch of UHBR ejector simulator

2.2 Test condition

The MSTOL model was tested in the WT at the flow velocity of V= 40 m/s (Mach number of M=0.13) and Reynolds number of Re= $0.89 \cdot 10^6$ based on the MAC. Forces and moments are measured with the AV-102 external six-component balance system. The model with ejector simulators is connected to AV-102 balance system by strip suspension. The model was mounted in an inverted position due to AV-102 balance system requirements. The tests in the range of angles of attack (AoA) of α = -3÷22° measured from fuselage reference line at a constant side slip angle of β=0° were performed. For the purpose of the exception of air supply system influence on AV-102 readings compressed cold air is supplied to the model through system flexible hosepipes and profiled air duct strut, which is connected with model through an internal air hinge. The MSTOL scale model in the T-102 WT is shown in Figure 4. The coefficients of aerodynamic forces are referred to the free-stream dynamic pressure and the wing area. The coefficient of longitudinal moment related to the MAC is calculated from the center of gravity. The center of gravity is located at 25% MAC. The test results are made standard corrections adopted in the T-102 WT, as well as corrections obtained in special tests to the effect of the air duct strut and the compressed air supply system.

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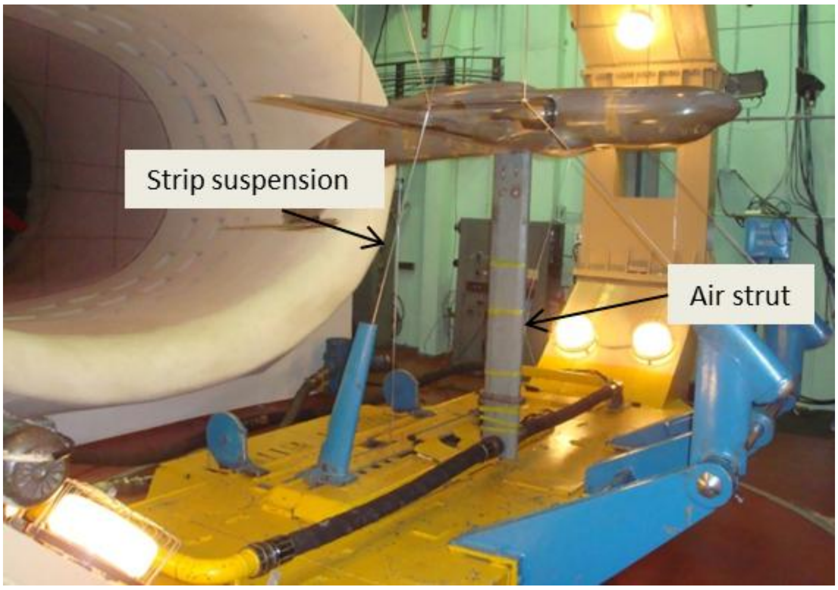

Figure 4: The MSTOL scale model in the T-102 WT

Methodical tests to determine the dependence of the thrust of ejector engine simulators of T_0 on the total pressure change in the range from 1 to 7 atm were carried out for the MSTOL model at the cruising configuration without WT flow at zero AoA. The components R_y and R_x of the total aerodynamic force of R acting on the model with running engine simulators were measured using AV-102 and determined with:

$$R = \sqrt{R_y^2 + R_x^2} \tag{1}$$

The thrust of ejectors simulators of T_0 experimentally determined without WT flow is given in Figure 5. The engine thrust coefficient is known as $C_T = T_0/q_\infty S$, where T_0 – measured simulators thrust, S – the wing area, q_∞– free-stream dynamic pressure.

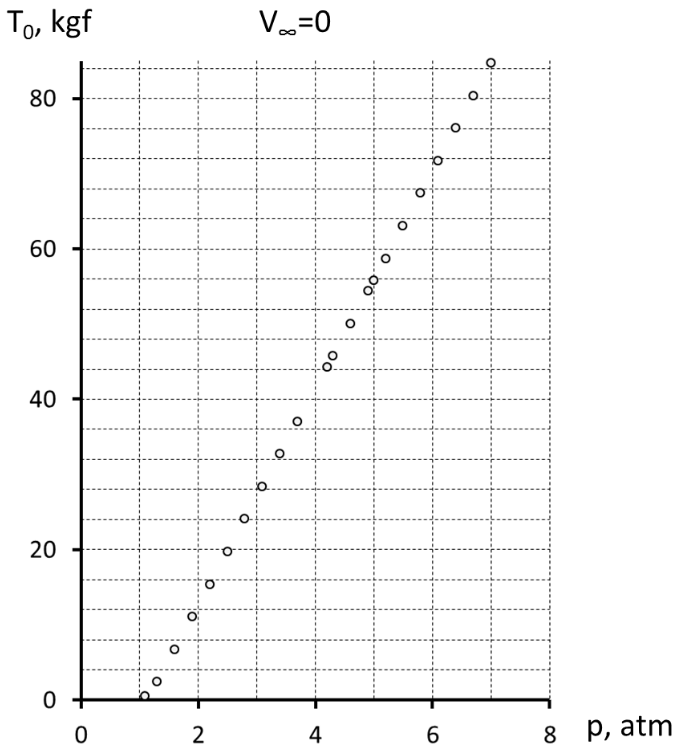

Figure 5: Total pressure versus thrust of the engine simulators

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The jet turning angle θ_j = arctan R_y/R_x and the jet momentum loss coefficient $\eta = R/T_0$ are the main parameters that determine the deflection efficiency of exhaust flows when the wing with extended flaps blowing. The jet momentum losses are related to turning exhaust flows by flaps (loss of friction, vortex formation and spreading jets along the wingspan). The values of these parameters were also obtained for model with extended flaps without WT flow zero AoA. The jet turning angle and the jet momentum loss coefficient as functions of value of T_0 is shown in Figure 6. These tests have shown that the addition of the engine thrust in the investigated range slightly influence on the jet turning angle and jet momentum loss coefficient. However these values significantly depend on the deflection angles of flaps. For MSTOL model in the takeoff condition, the jet turning angle is approximately 25° and in landing condition is roughly 58° (see Figure 6a). The value of jet momentum loss coefficient grows with increasing flaps deflection, which is approximately 10% and 35% for the takeoff and landing configurations, respectively (see Figure 6b). Deflection of the spoiler droop at δ_{sd} = 16° on model in landing configuration totally covered the fore flap slot which leads to a reduction in the jet turning angle and an increase in the jet momentum loss coefficient.

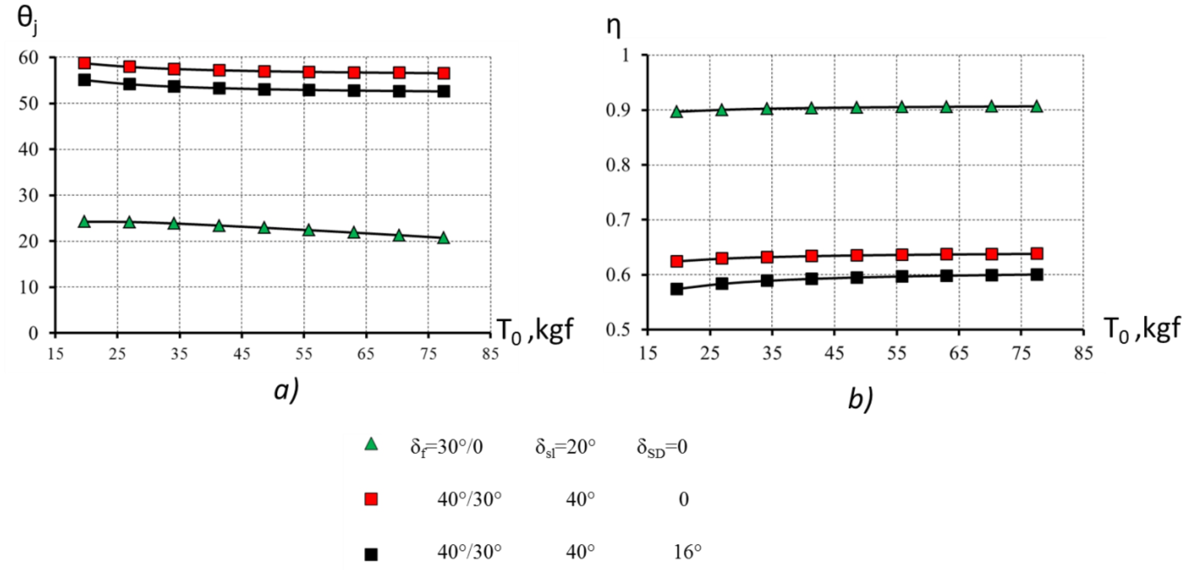

Figure 6: Simulator thrust versus the jet turning angle (a) and the jet momentum loss coefficient (b)

3. Test results

The effect of high-lift wing blowing by engine simulator exhaust flows ($C_T \approx 1$) at the takeoff and landing configurations of the twin-engine model without tail is shown in Figure 7. For comparison, Figure 7 also presents the model aerodynamic characteristics with retracted high-lift devices without blowing. As can be seen, the high-lift wing blowing by engine jets leads to a significant increase in the wing lift at both takeoff and landing configurations (see Figure 7a). For example, large flaps deflection corresponding the landing condition, the value of the maximum lift coefficient rises from 2.3 at power off (C_T = 0) to 4.6 at power on (C_T = 0.9). The model polar has shifted to the direction of decreasing the drag coefficient due to improved flow of the wing with deflected high-lift devices and engine thrust (see Figure 7b). A significant improvement in the aircraft's polar at take-off configuration should be decreased the length of the take-off distance by reducing the running-up length and a greater glide slope angle. The relative value of the polar displacement of the model at the landing configuration is much smaller due to the large deflection angle of the engine jets (see Figure 6a) and the increase in jet momentum loss (see Figure 6b), as well as an increase in additional inductive drag due to the irregular distribution of the velocity circulation along the wingspan with intensive blowing of the inboard flaps by engine jets. This circumstance is favorable, because it should be able to have a lower landing speed and a high angle of the glide path and, accordingly, a shorter landing distance.

Figure 8 shows that the increase in engine thrust coefficient leads to intensively grow values of the increment lift coefficient at both the take-off and landing configurations. The increasing lift at takeoff and landing conditions of aircraft model is due to suppression of flow separation over flaps, the supercirculation effect and the effective deflection of engine exhaust flows. The main part of the total increment of the lift coefficient of ΔC_L is created due to

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the favorable impact of engine jets on the flow around the wing with deflected flaps and the effect of supercirculation, which is determined by the value of the aerodynamic increment of lift coefficient:

$$\Delta C_{LA} = \Delta C_L - \eta \cdot C_T \cdot \sin(\alpha + \theta_j) \quad (2)$$

The value of the aerodynamic increment of lift coefficient of ΔC_{LA} of the MSTOL model in the landing configuration at zero AoA is approximately 70% of the total value of ΔC_L at the thrust coefficient of $C_T = 0.9$ (see Figure 8a). The value of the increment of the maximum lift coefficient in the landing configuration of the MSTOL model increases from $\Delta C_{Lmax} = 1.0$ without blowing ($C_T = 0$) to $\Delta C_{Lmax} \approx 3.4$ at $C_T = 0.9$ (Figure 8b).

An effective means of lift increasing and its control at takeoff and landing modes is the use of the spoiler droop (see Figure 2). The application effectiveness of this device on the model with blowing ($C_T \approx 1$) is shown in Figure 9. Figure 8 is focusing on the lift and pitching moment coefficients as a function of AoA. When flaps are blown by jets of engines, the SD deflection to the optimal angles gives rise the lift by 10 – 15% at AoA of α = 6 – 10º. In this case, the behavior of $C_L(\alpha)$ curve is almost a linear dependence in the investigated range of AoA due to the suppression of the flow separation on the wing blown by jets of engines (see Figure 9). The SD deflection at angle δ_{SD}=8º for the model at take-off configuration (δ_f = 30º/0; δ_{sl}= 20º) leads to increase the value of lift coefficient by 13% at AoA of α = 6 – 8º. At the same time, the value of the maximum lift coefficient practically does not change and the critical angle of attack decreases from 17° to 16°, which is due to the flow separation on the SD upper surface at high AoA. For the model at landing configuration (δ_f = 40º/30º; δ_{sl}= 40º), the lift coefficient increment is $\Delta C_L \approx 0.4$ due to SD deflection at angle δ_{SD}=12º at landing AoA of α = 10°, and the maximum lift coefficient rises up to 4.8. This is phenomena to be explained by the effect of supercirculation, which to delay flow separation at landing configuration. The SD deflection at landing configuration also has a positive effect on the polar behavior (see Figure 9b). The pitching moment of the model practically does not change due to the SD deflection (see Figure 9a). This important effect should be used in development of the aircraft control system.

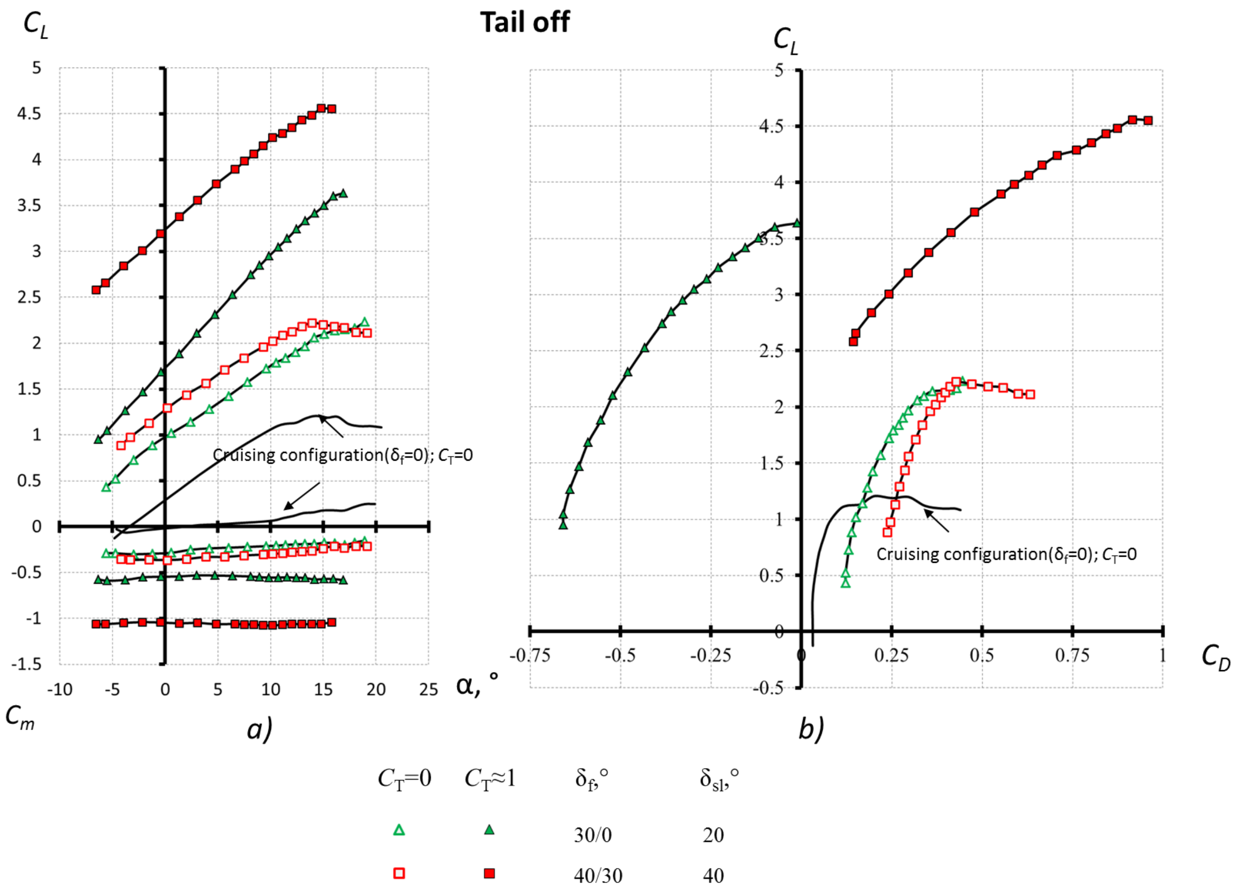

Figure 7: Influence of the wing blowing by exhaust flows on the aerodynamic characteristics of the model

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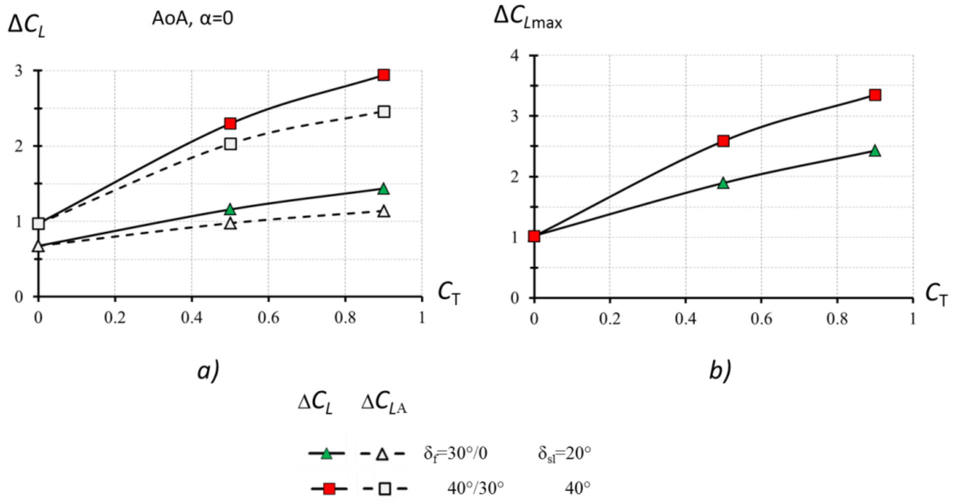

Figure 8: Influence of flaps blowing by exhaust flows on the lift coefficient of the MSTOL model

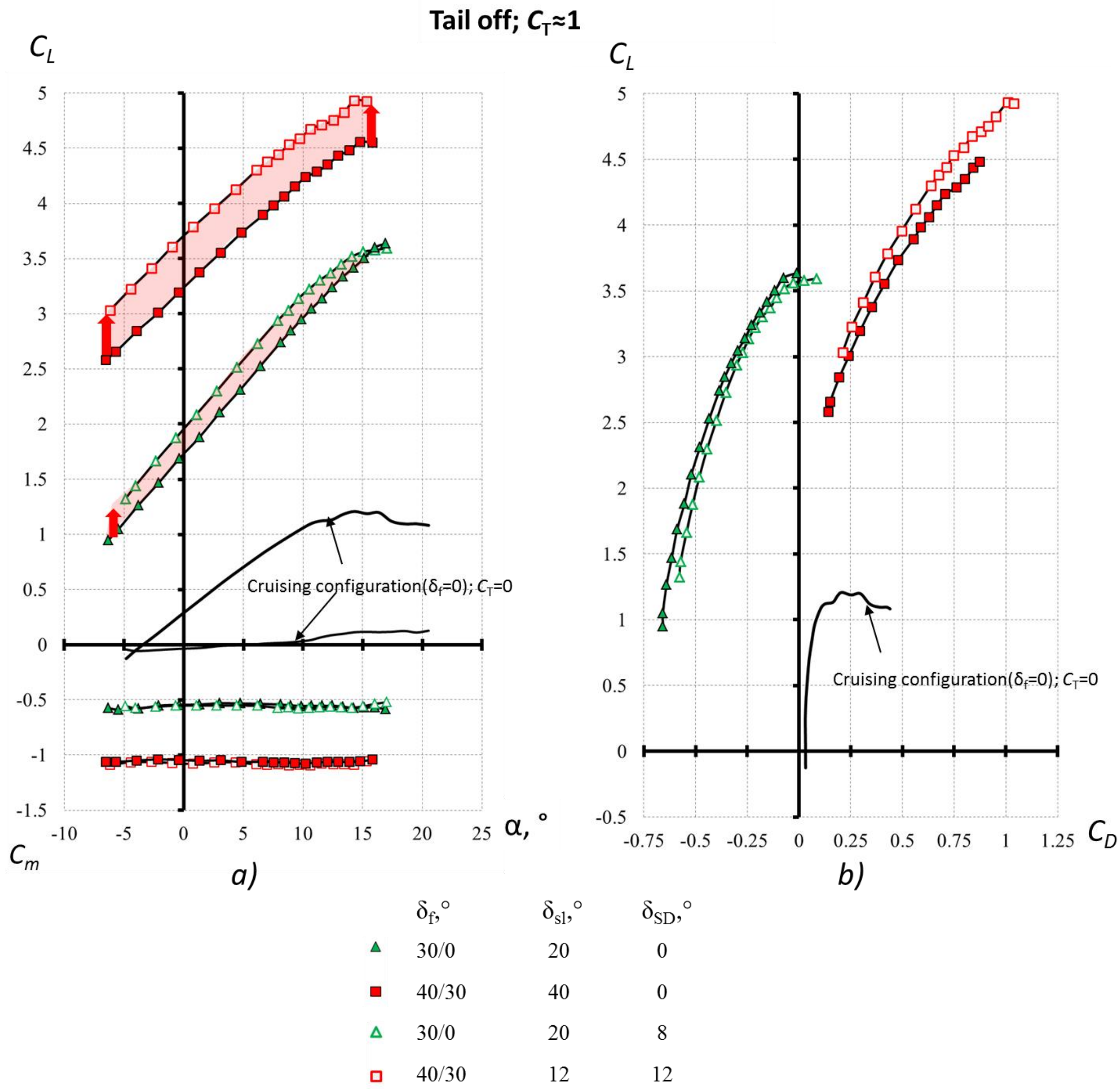

Figure 9: Effect of SD deflection on the aerodynamic characteristics of the MSTOL model

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Aerodynamic characteristics of the MSTOL model with a horizontal stabilizer deflected by an angle of φ_{HT} = -6° are shown in Figure 10. Experimental results were found that the model at the take-off configuration is statically stable in the longitudinal channel with the center of gravity located at 25% of the MAC and a relatively small diving moment can be trimmed by the elevator. The high-lift wing blowing at the landing configuration slightly reduces the margin of longitudinal static stability and creates a significant diving moment. A large level of negative pitching moment is associated with both the flow features of the high-lift wing blown by engine jets and due to the intense flow separation on the lower surface of horizontal stabilizer at large angles of downwash. To ensure the longitudinal stability of the model in these conditions, it is necessary to increase the efficiency of the horizontal stabilizer through the use a droop nose or slat on its leading edge in combination with an increase in horizontal tail volume ratio of A_{HT} from 0.736 to 1.3 – 1.5 (typical for STOL aircraft with PLS) and use a highly efficient two-hinge elevator [3], [7]. It should be noted that the deflection of the slat at δ_{sl}=40° without blowing leads to a significant drop of C_{Lmax} caused by flow separation on the slat.

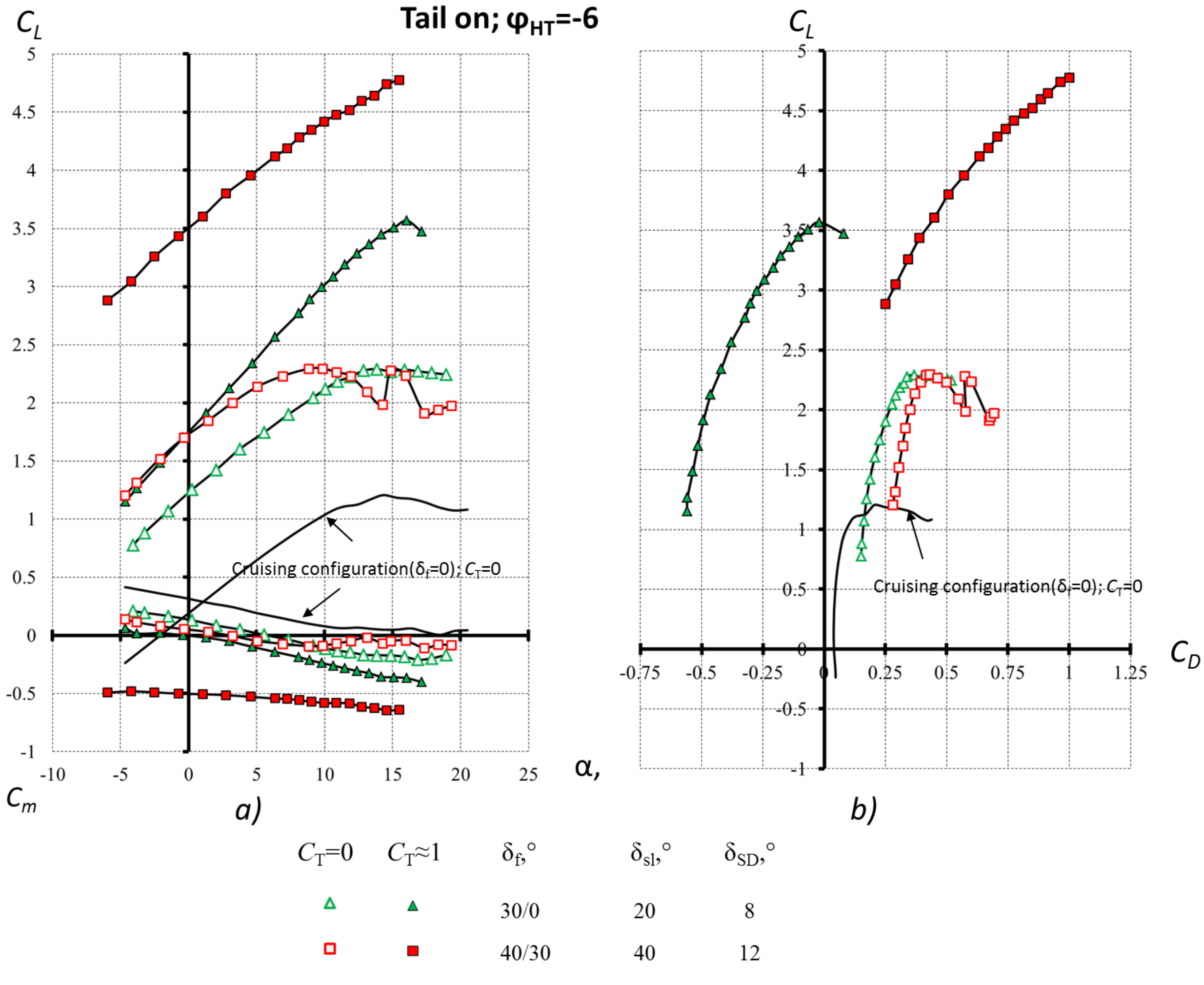

Figure 10: Aerodynamic characteristics of the MSTOL model with tail

4. Comparison of the aerodynamic characteristics model versions with two and four engines

It is practically important to compare the efficiency of the EBF on model versions with two and four engines at equal values of the engine thrust coefficient. A comparison of the longitudinal aerodynamic characteristics of MSTOL model with two and four engines at cruise and landing configurations at C_T = 0 (power off) is shown in Figure 11. As can be seen, the level of lift on both model versions are approximately the same, but on the model with two nacelles, the maximum lift coefficient is higher than on the model with four nacelles in both cruising and landing

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configurations (see Figure 11a). Lower level increment of maximal lift coefficient of ΔC_{Lmax} of four-engine model is associated with the adverse effects of nacelles on the flow around the wing at high AoA. Reducing the number of nacelles leads to a corresponding decrease in aerodynamic drag (Figure 11b).In addition, the twin-engine model with extended flaps and slats reduces the diving moment, which facilitates the solution of the problem of its longitudinal stability.

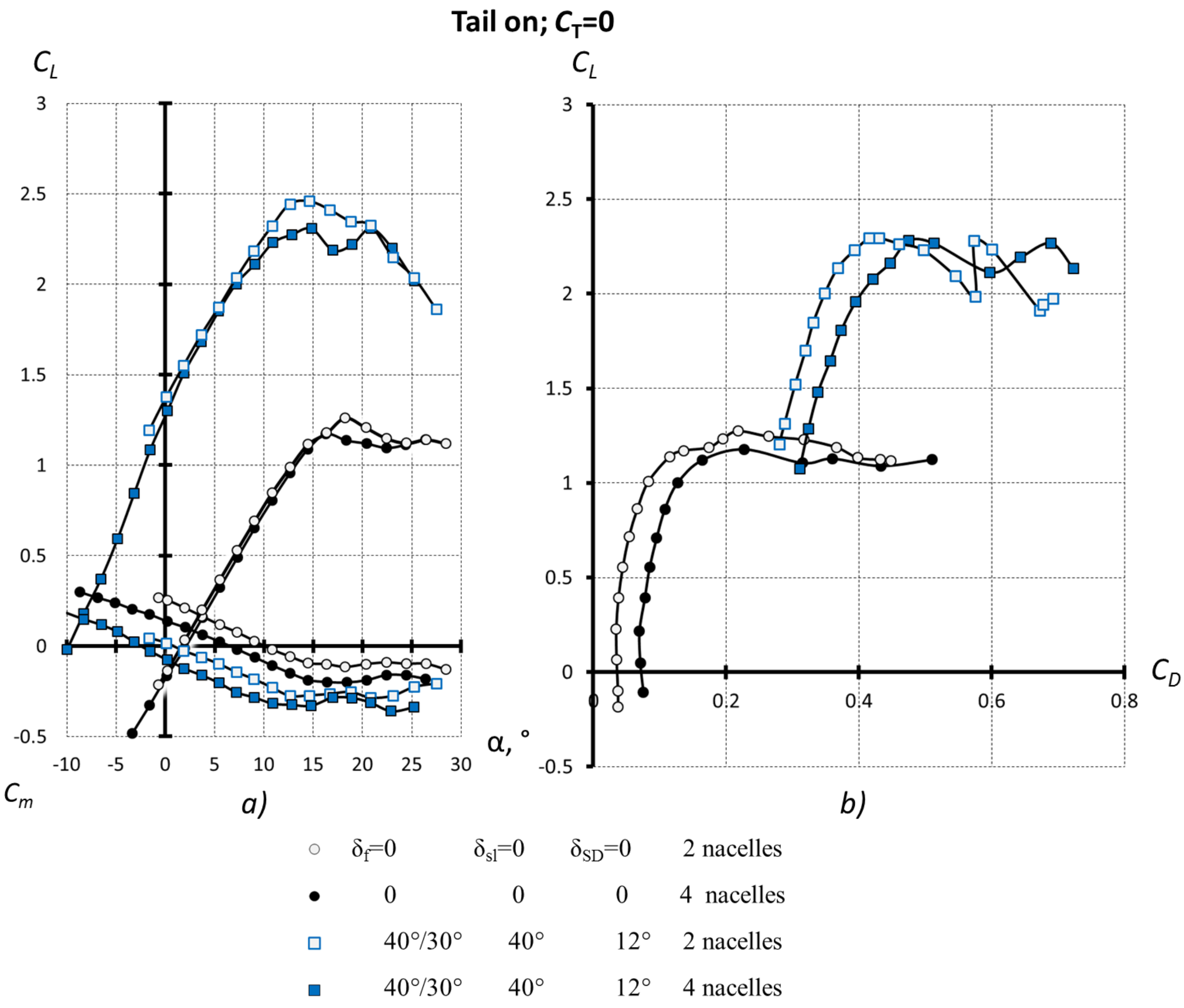

Figure 11: Comparison of the aerodynamic characteristics of the model versions with two- and four-engine

Comparison of the efficiency of wing blowing by exhaust flows of two and four engines is given in Figure 12. These test results show that both model versions provide approximately the same increment of the lift coefficient as at zero AoA (see Figure 12a) and at maximal lift coefficient mode (Figure 12b) at the same values of the engine thrust coefficient. This important result indicates the possibility of obtaining high values of the lift coefficient on twin-engine aircraft due to the intensive blowing of the root parts of the wing. The increase in wing lift on the twin-engine model is accompanied by a higher increase in drag coefficient at the landing configuration (Figure 12c) and a lower increment of the pitching moment coefficient to dive (Figure 12d), than on the four-engine model. Reducing the pitching moment coefficient facilitates the problem of longitudinal stability of the aircraft, and the increase in drag coefficient at the landing configuration allows taking a steeper flight path and, accordingly, reducing the required length of the landing distance.

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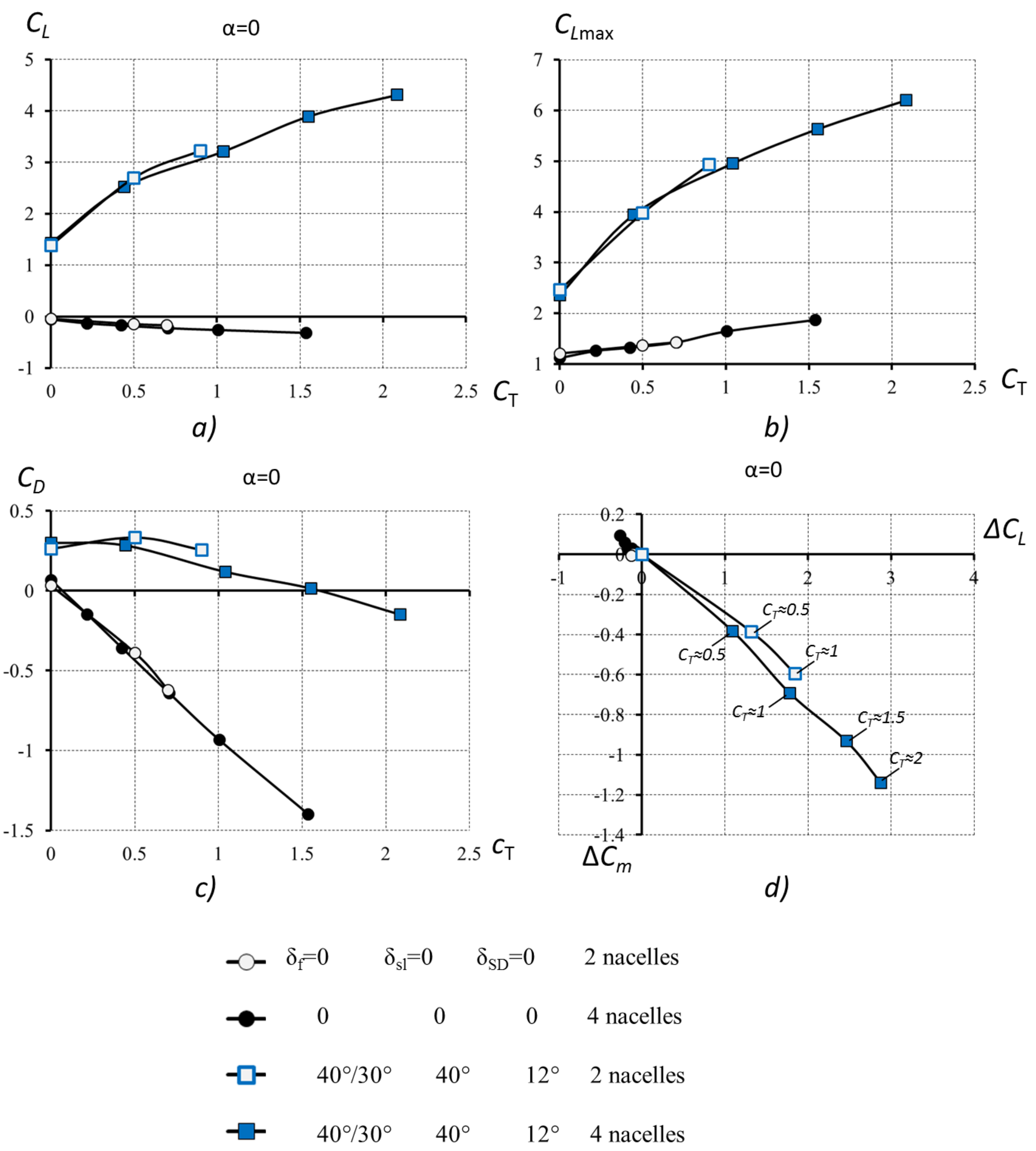

Figure 12: Comparison of the aerodynamic characteristics of the model versions with two- and four-engine with blowing

Conclusion

In general, the experimental studies have shown the principal possibility of using the EBF for increasing lift of the twin-engine transport aircraft required for providing STOL capability. Blowing by exhaust flows of two engines of the lower surface of the wing and flaps with the spoiler droop is an effective means of increasing lift at takeoff and landing flight modes. The obtained values on a twin-engine aircraft model of the lift coefficient are close to the corresponding values on a four-engine aircraft model, and the aerodynamic drag is much less on a twin-engine aircraft with the same values of the engine thrust coefficient. To ensure a longitudinal stability in case of intense wing blowing at landing condition, it is necessary to increase horizontal tail volume ratio in combination with using

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the droop nose or the slat on the leading edge of horizontal stabilizer and used a high-efficiency double-hinged elevator.

References

[1] Petrov A.V. 2012.Aerodynamics of STOL airplanes with powered high-lift systems. In: *28-th Congress of the Congress of the International Council of the Aeronautical Sciences.* ICAS 2012-9.5.2.

[2] Petrov A.V. 2003. Aerodynamics of transport airplanes. In: *TSAGI—the Basic Stages of Scientific Research 1993–2003*. 104–116. (in Russian)

[3] Petrov A.V. 2018. Aerodynamics of Short Takeoff and Landing Transport Airplanes with Powered Lift Systems. Innovatcionnoe Mashinostroenie. (in Russian)

[4] Pavlenko O., Petrov A., Pigusov E. 2018. Concept of medium twin-engine STOL transport airplane. In: *31-th Congress of the International Council of the Aeronautical Sciences*. ICAS2018-0104.

[5] Pigusov E. 2019. Experimental study of ground effect on the aerodynamic characteristics of twin-engine STOL transport aircraft. In: *54th 3AF International Conference on Applied Aerodynamics AERO2019.*

[6] T-102 TsAGI wind tunnel. URL: http://www.tsagi.ru/experimental_base/aerodinamicheskaya-trubs-t-102/

[7] Balabuyev P.V., Bogdanov O.K., Kudryavtsev V.A., Pustovoytov V.P. 2002. An-70 STOL aircraft characteristics at high angles of attack and takeoff and landing characteristics. In: *23-rd Congress of International Council of the Aeronautical Sciences.* ICAS 2002-P1.