Theory and Test of Flow Mixing for Turbofan Engines

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For certain applications of advanced turbofan engines, it is advantageous to transport various amounts of the gas-producer kinetic energy to a second stream. The reasons for and the advantages and methods of gasdynamic energy transport (mixing process) are explained with different examples. The optimum layout of fan engines with and without mixing is discussed, and the influence of partial mixing on performance is pointed out. Theoretical considerations, which show that the thrust of bypass turbojet engines may be increased by mixing the hot exhaust jet with the cold bypass flow, are compared with experimental data. Tests of three mixer configurations were conducted on an experimental rig with very accurate thrust measurements and flow profile instrumentation at different sections of the mixing chamber. Results of these experiments are discussed.

Nomenclature

c = velocity
E = energy usable for producing thrust
$\mathfrak{E}$ = ratio of transported energies
H = flight height
M = Mach number
p = pressure
S = thrust
s' = thrust for $\dot{m}_I$ = 1 kg/sec
t = temperature
z = bypass ratio
π = compression ratio
η = efficiency

Subscripts and superscripts

∞ = undisturbed atmosphere
a = final nozzle exit
da = external diameter
0 = without mixing
t = total state
Tr_{mech} = mechanically transported energy
Tr_{gd} = gasdynamically transported energy
* = referred to the critical condition
1 = primary flow at mixing chamber entrance
2 = secondary flow at mixing chamber entrance
3 = perfect mixing in the mixing chamber
I = in the primary flow after final nozzle exit
II = in the secondary flow after final nozzle exit
III = complete mixing
BK = combustion chamber
GE = gas producer
TL = nonbypass engine
ZTL = bypass engine
ZTL_0 = bypass engine with no mixing
ZTL_m = bypass engine with mixing
UK = diverter chamber
MK = mixing chamber
SD = final nozzle

1. Introduction

AERODYNAMIC and technological research and development make it possible today to build engines of higher specific output than previously, i.e., to achieve a greater conversion of heat from the fuel into kinetic energy of the jet, in smaller and lighter engines.

At medium and low flying speeds, and particularly when the aircraft is static, an exhaust jet of relatively small mass and high velocity is not always advantageous for producing thrust, because of high energy losses at the jet outlet and associated poor exploitation of kinetic energy of the exhaust jet for production of thrust. Moreover, a gas jet with a high outlet velocity produces a high noise level, leads to a not insignificant ground erosion when directed vertically downwards, and magnifies the problem of recirculation for long hovering periods. These problems become more significant with progressive technological development, i.e., faster and hotter exhaust jets.

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2. Theory

2.1 Energy Transport in Aeroengine System

In order to make use of kinetic energy produced in the internal process for production of as high a thrust as possible, the low-mass, high-velocity jet must be converted economically into a gas jet of high mass and low velocity. Such a jet conversion can be achieved 1) by mechanical means with turbine, shaft, and compressor, and 2) by gasdynamic means with mixer and mixing chamber (ejector). At flying speeds substantially higher than takeoff speeds of present-day transport aircraft, mixing losses in bypass engines in which the transfer of energy from the primary to the secondary stream is achieved by gasdynamic means alone, are too great. In a bypass cruise engine that employs mixing, therefore, the energy is transferred by mechanical as well as gasdynamic means. With the mechanical transfer of energy which occurs

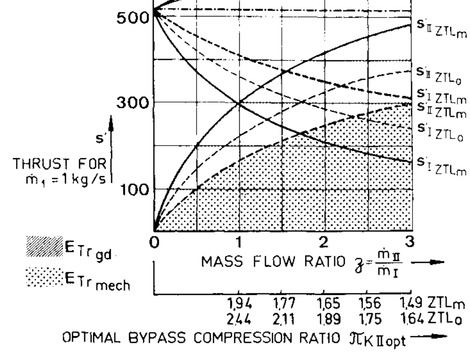

Fig. 1 Change in thrust for the optimum energy transport and given bypass ratios. (H_∞ = 6 km, M_∞ = 0.8, t_{BK} = 900°C, π_{KI} = 7.)

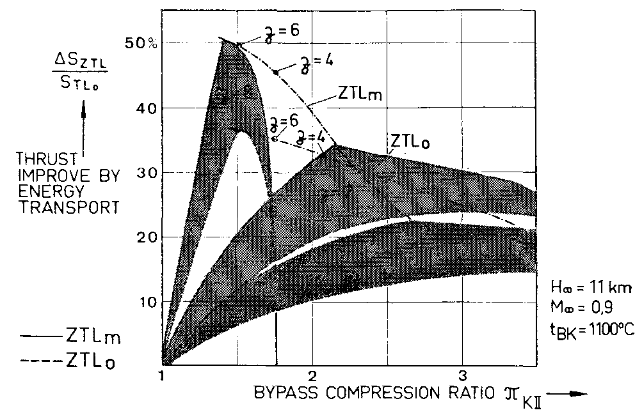

Fig. 2 Thrust increase of bypass engine with and without mixing over the simple jet engine. (H_∞ = 11 km, M_∞ = 0.9, t_{BK} = 1100°C.)

first, the means is provided of creating suitable initial conditions for the mixing process.

Figure 1 shows how thrust in the primary flow is decreased and thrust in the secondary flow is increased by optimum energy transport as a function of bypass ratio for the fan engine with and without mixing. At the extra abscissa is written the optimum fan compressor ratio; the two upper curves show the total thrust increase for mixed- and unmixed-flow bypass engines with increased mechanical and gasdynamic energy transfer.

2.2 Optimum Layout of Fan Engines with and without Mixing

In mixed-flow fan engines the amount of mechanical energy transport is less than in simple fan engines without mixing. In the mixed-flow bypass engine only enough energy is transported from the inner cycle with turbine and compressor to the outer cycle, that the difference of the velocities at the entrance into the mixing chamber is not high and thus the mixing losses are limited.

The efficiency of gasdynamic energy transport must be better than the efficiency of mechanical energy transport in order to get a thermodynamic advantage by mixing. The difference in the optimum fan pressure ratio for a given mass flow ratio, the gain in thrust or efficiency, and the sensitiveness for a nonoptimum layout are shown in Fig. 2 for both fan engines; the gain by mixing increases with the mass flow ratio. The area of gain is higher, but much more narrow, as for small mass flow ratios.

The sensitiveness for a deviation from the optimum layout of the fan pressure ratio is very great for large mass flow ratios;

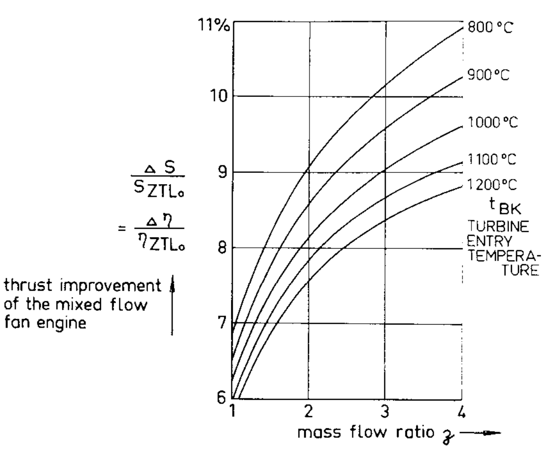

Fig. 3 Maximum gain by mixing for ideal mixing conditions. (H_∞ = 11 km, M_∞ = 0.9.)

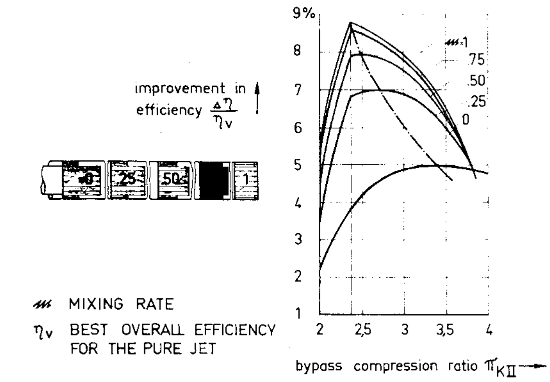

Fig. 4 Influence of partial mixing. (H_∞ = 11 km, M_∞ = 0.8, t_{BK} = 900°C, π_{KI} = 11, Z = 1.)

and for a mixed-flow fan engine it is even greater than for an unmixed-flow fan engine.

2.3 Maximum Gain by Mixing for Ideal Mixing Conditions

The relative gain by mixing for ideal conditions is shown in Fig. 3. The absolute gain by flow mixing before the final nozzle increases with the turbine entry temperature. The absolute and the relative gain by mixing, i.e., the postulated optimum fan pressure ratio for the mixed- and the unmixed-flow fan engine, increases with greater mass flow ratio. The cruise thrust gain through mixing can be as high as the pod drag loss.

2.4 Influence of Partial Mixing

In aeroengines a complete mixing cannot be realized because of limited jet pipe length. As is shown in Fig. 4, a 50% mixing brings a 78% improvement in the maximum theoretical efficiency. The efficiency of fan engines with different mixing degrees m is related in Fig. 4 to the pure turbojet, which is an optimal layout for the assumed cruising conditions (not identical to the layout of the primary cycle of the fan engine).

2.5 Application of Fan Engines with Mixing: Advantages for Lift and Cruise Engines

The advantage of mixing in cruise fan engines is easy to see in Fig. 3, especially when taking into account that the relative gain is increased if pod drag is considered also. Pod drag is about equal for both engines for low bypass ratios. The only question is, how much mixing is practical, because a bypass duct in full length can bring losses for a relative large mass flow which can be avoided with a short bypass ducting.

In Fig. 5 is shown the optimum mechanical and gasdynamic energy transport as a function of the compression ratio of the primary cycle. There is a big difference between mechanical

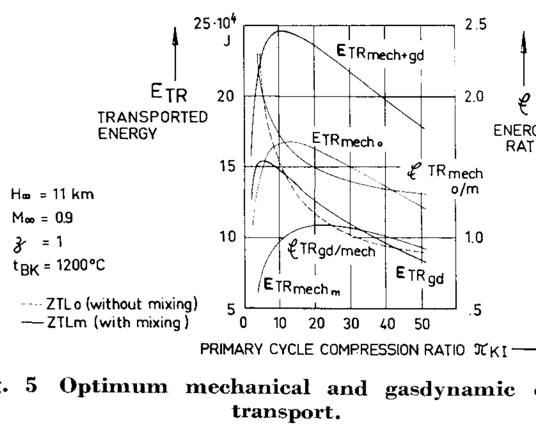

Fig. 5 Optimum mechanical and gasdynamic energy transport.

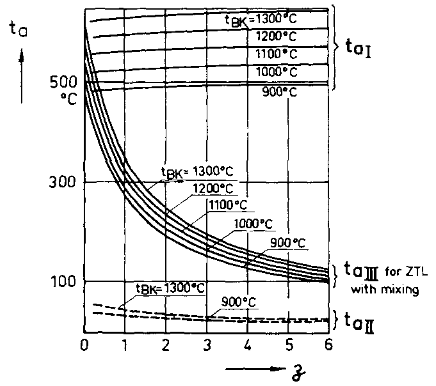

Fig. 6 Final nozzle exit temperature for different fan engines. (ISA; $H_\infty = 0$, $M_\infty = 0$.)

and over-all energy transport of the mixed- and unmixed-flow fan engines.

The ratio of gasdynamic and mechanical energy transport of the mixed-flow fan engine, called $\mathfrak{E}T_{gd/mech}$, is decreasing; this means that the absolute thrust difference between the mixed- and unmixed-flow fan engine is decreasing for increasing primary cycle compression ratio.

Thus, the importance of flow mixing in a fan engine is great if (e.g., for reasons of engine weight of the inner cycle compressor) a relative low compression ratio is to be chosen. This is so in the case of lift engines.

The outlet temperature of the mixed-flow fan engine is rapidly decreasing with greater mass flow ratios (Fig. 6). This fact is very important for lift engines because of the following reasons: 1) recirculation and hot gas ingestion, 2) ground erosion, 3) noise level, and 4) personal near the aircraft. Further applications for mixed-flow fan engines are: 1) helicopter with tip-drive rotor, 2) turbojet with reheat, and 3) turboramjet engine.

3. Experiment

3.1 Reasons for the Tests

Although the influence of limited mixing-chamber cross-sectional area and of partial mixing was treated mathematically, it was not possible to deal mathematically with the mixing process as a function of mixing chamber length. Apart from the mathematical relationships that govern the mixing process, the effects of the following were not accounted for in the calculations: 1) mixer geometry, 2) velocity and temperature profiles, and 3) friction losses in the mixer. The experimental investigation is intended to provide, for geometrically different mixers, a relationship between the degree of mixing and mixing-chamber length, and to give information on the actual thrust gain due to mixing for a given kinetic energy in both streams and for various mixing-chamber lengths.

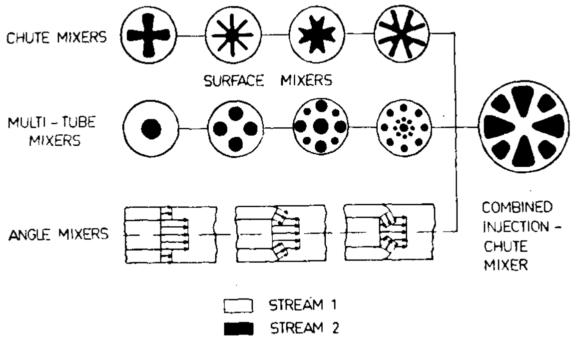

Fig. 7 Diagrammatic sketches of various mixer configurations.

3.2 Design of the Test Rig

According to the results of the theoretical studies,[1,2] the absolute thrust gain due to mixing is higher, the higher the mass flow, the higher the bypass ratio, and the higher the combustion end temperature. The optimum design of a bypass engine with mixing is obtained when the bypass compressor and bypass turbine transmit mechanically just so much energy that the total pressures of the two streams before mixing are approximately of equal magnitude. The test rig was designed to simulate this condition.

The design was such that the mass flow of the primary stream was 1 kg/sec and the secondary air mass flow 3.2 kg/sec. The total mass flow was thus 4.2 kg/sec and the bypass ratio was $z = 3.2$. The total pressure of both streams was equal in magnitude, and hence the Mach numbers at the inlet to the mixing chamber were also equal. The ratio of the temperatures of the secondary and primary streams was 0.32 and hence corresponded to the temperature ratio of a bypass engine with mixing, which, at a bypass ratio of $z = 3$ and a turbine entry temperature of 1200°C designed for optimum thrust, is operating at 11-km (36,000 ft) altitude and an aircraft Mach number of $M_\infty = 0.9$. The mixing chamber used in the test had a diameter of 256 mm.

3.3 Test Schedule and Execution of the Tests

3.3.1 Mixing process of the design point

If the objective is to obtain the highest possible degree of mixing with the short mixing-chamber lengths available for aircraft gas turbines, as exist in bypass engines, then it is necessary to apply suitable methods to accelerate the mixing process. The gasdynamic transfer of energy is effected by turbulent exchange. For rapid mixing a high degree of turbulence, uniformly distributed over the mixing-chamber cross section, is desirable. This can be produced more rapidly by (Fig. 7):

1) Increasing the difference in velocity of the two in-flowing gas streams; this method increases the momentum loss due to mixing and hence reduces the possible gain.

2) Instead of using the simplest form of mixer, consisting of concentric cylindrical flow ducts (axial flow mixer), letting the bypass stream meet the stream from the gas-producer portion at an angle (angle mixer).

3) A more effective method is to enlarge the contact surfaces of both gas streams at the inlet to the mixing chamber by corrugating the rim of the primary nozzle and thus increasing the tractive force of the driving stream. The distinguishing feature of the surface mixer is that, with this mixer, the ratio of the perimeter of the inflowing primary stream to the mixing-chamber cross-sectional area becomes greater, the more the primary stream is divided up (multitube mixer) or channeled (chute mixer).

The foregoing methods can be combined with each other; a combination of methods 2 and 3 leads to the so-called pocket mixer. The distinguishing feature of the optimum mixer is

Fig. 8 Axial-flow mixer, injection mixer, and chute mixer.

the highest possible degree of mixing achieved in the shortest mixing chamber with the minimum additional mixing losses.

Three mixers were designed and built for the experimental investigation (Fig. 8): 1) an axial flow mixer, 2) an angle mixer for $\beta = 30°$, and 3) a chute mixer with four double chutes and with a perimeter 3.4 times greater than the axial flow mixer (see Fig. 9). The effect of mixing was investigated for the three configurations, according to the calculated optimum conditions. In order to be able to compare the thrust of the engine with mixing with the thrust of the engine without mixing, measurement of thrust was carried out with the hot and cold gas streams expanding separately to ambient pressure (Fig. 10, upper left). At the test rig design point the critical Mach numbers at the inlet to the mixing chamber are 0.18; hence, with a primary stream temperature of 700°C and secondary stream temperature of 35°C the absolute inlet velocities are 100 and 60 m/sec. The critical Mach number at the final nozzle outlet is 0.8 (≙314 m/sec).

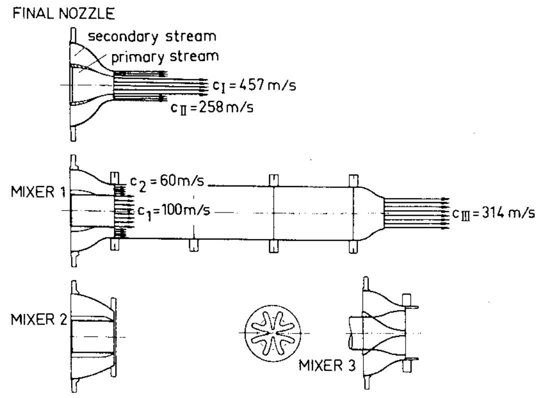

Fig. 10 Four cases investigated at the test bed design point. From top to bottom: two separate final nozzles, axial-flow mixer with three mixing chamber segments, and final nozzle, angle mixer, chute mixer. (Design of test rig: $\dot{m}_1 = 1$ kg/sec, $t_1 = 700°C$, $t_2 = 40°C$, $M_1{}^* = M_2{}^* = 0.18$, $Ma\ III^* = 0.8$, $z = \dot{m}_2/\dot{m}_1 = 3.4$.)

3.3.2 Mixing process at higher mixing-chamber inlet Mach numbers

In operative engines the Mach number of the gas streams entering the mixing chamber will lie at least between 0.2 to 0.25 or above, in order to avoid additional losses due to deceleration of the primary stream beyond the turbine in a diffusor.

As the mixing-chamber inlet velocities become greater, the time spent by the gas and the air in the mixing chamber becomes less, and the difference in the velocities increases for the same bypass ratio and optimum bypass compression ratio. Hence, the losses due to friction on the walls of mixer and mixing chamber, and the mixing losses themselves, also increase. A substantial increase in mixing-chamber inlet Mach number can be achieved on the test rig only by leaving out the final nozzle. For this case the inlet Mach number is $M_1{}^* = M_2{}^* = 0.37$.

The measurement of thrust, which is easily accomplished, and the profile investigations within the mixing chamber are carried out separately. Following this operation, the exhaust jet profile is measured for various angular positions by means of the probe rake, positioned behind the final nozzle.

3.4 Discussion of the Test Results

3.4.1 Temperature profile in the mixing chamber for the axial flow mixer

Figure 11 presents the measured temperature distribution for a critical inlet Mach number of both streams of $M^* = 0.37$. The angular setting of the rake is plotted along the abcissa of each of the diagrams. The 15 probes are numbered from the inside outwards, probe no. 2 lying exactly on the axis of the mixing chamber. Results are given for four mixing-chamber stations, the associated mixing factors being 31% for a mixing-chamber length/diameter ratio of 1.95, 47% for a nondimensional mixing-chamber length of 3.12, and 57% for a mixing-chamber length of approximately 4 mixing-chamber diameters. The diagram shows clearly how the cold stream slowly heats up and the hot stream cools correspondingly.

A series of four diagrams (Fig. 12) show the isotherms over a section of the mixing chamber for mixing-chamber lengths of 40, 60, 80, and 234% of the mixing-chamber diameter. The regions of different temperatures are indicated by different degrees of shading. The shading becomes more dense, and the area darker as the temperature rises.

In the presentation, the primary stream has the form of the end section of the chute mixer at a mixing-chamber length of zero. The hot zone contracts 100 mm downstream of the mixer and (section 2) is already divided by the cold stream at a mixing-chamber length of 150 mm. At a mixing-chamber length of 200 mm there are four hot zones arranged around the mixing-chamber axis and also four hot zones in contact with the wall of the mixing chamber, corresponding to the number of double-lobe chutes. The fact that in this test the mixing-chamber walls became hotter than during the profile measurements with the axial flow and angle mixers

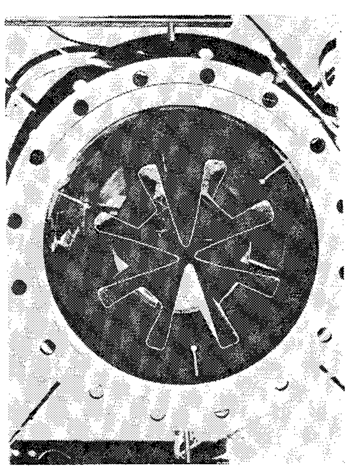

Fig. 9 Installed chute mixer with mixing chamber.

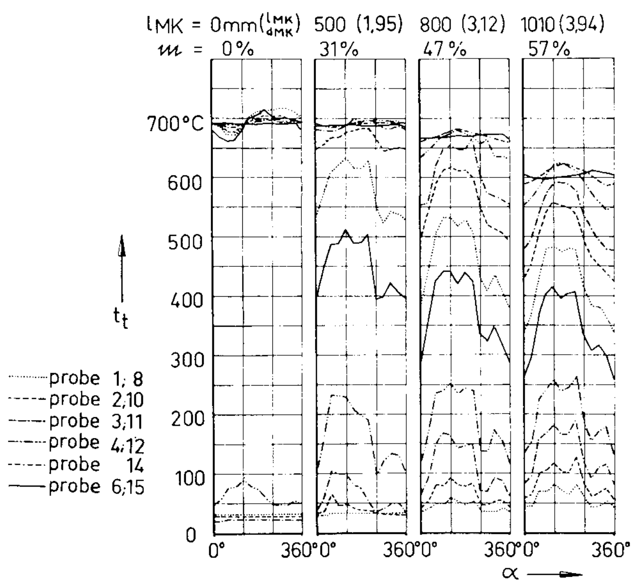

Fig. 11 Temperature distribution at four different mixing chamber sections for the axial-flow mixer. The critical inlet Mach is $M_{1,2}{}^* = 0.37$.

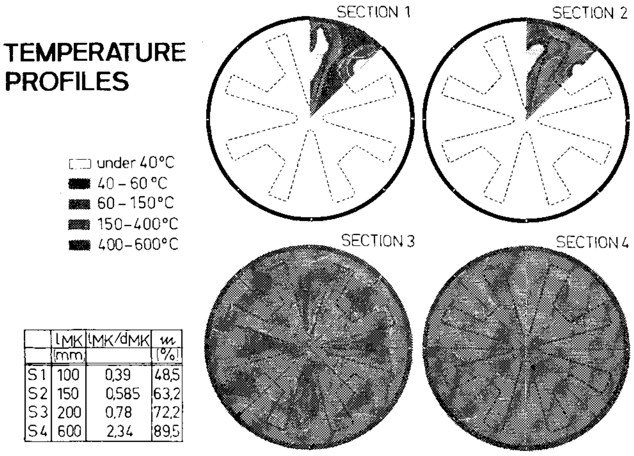

Fig. 12 Isotherms at four different mixing-chamber sections for the chute mixer.

was indicated during the test by discoloration of the first two pairs of flanges.

In the 4th section the eight hot regions become still cooler, and the degree of mixing is almost 90% at a mixing-chamber length of 600 mm, which corresponds to a mixing-chamber length/diameter ratio of 2.34.

It is interesting to note that the originally radial spread of the hot stream deforms during mixing and changes to an extension in a circumferential direction.

3.4.2 Degree of mixing and thrust gain for all three mixers

The mechanism of turbulent mixing is not known, and hence it is not possible to calculate beforehand the conditions at various sections of the mixing chamber. The experimental investigation shows how the mixing proceeds as a function of the mixing-chamber length. The criterion for the degree of mixing is the so-called mixing-rate factor. It is defined as the quotient of 1) the total energy actually given off to the higher-energy primary stream divided by the maximum transportable total energy or 2) the total energy actually absorbed by the lower-energy secondary stream divided by the maximum absorbable total energy with perfect equalization of states.

The variation of the mixing factor over the length of the mixing chamber provides an answer to the question of how rapidly the mixing takes place over the mixing-chamber length for selected inlet conditions. The required curves are shown in Fig. 13: 1) critical inlet Mach number $M^* = 0.18$ and axial-flow mixer, 2) $M^* = 0.18$ and angle mixer 3) $M^* = 0.18$ and chute mixer, 4) $M^* = 0.37$ and axial-flow mixer. The curves are divided by a line at a mixing-chamber length/diameter ratio of 2, since normally with aircraft gas turbines, mixing chambers longer than 2 mixing-chamber diameters are not practicable. For a mixing-chamber length of 1 diam, the mixing factors for an axial-flow mixer, an angle mixer, and a chute mixer are in the ratio 1:2:8, and for a mixing chamber of twice this length the corresponding mixing factors are 24, 35, and 88.5%, respectively.

In the case of the first two mixers investigated, the mixing-factor curve is linear over almost the whole mixing-chamber length investigated, whereas in the case of the chute mixer it is linear only up to a chamber length of ½ diam and is 12 times steeper than in the case of the other two mixers investigated. The mixing factor then increases less and less with increasing mixing-chamber length. The effectiveness of the chute mixer is substantially superior to that of the injection mixer.

The effect of a higher inlet Mach number was investigated with the axial-flow mixer. The velocity difference at the inlet, for assumed rectangular profiles, was 92 m/sec compared with 45 m/sec at the design Mach number.

Because of the severe turbulence at the start of the mixing chamber, the exchange process occurs more rapidly, i.e., the effect of the increased turbulence due to the larger velocity gradient between the two streams predominates over the shorter residence time of the gas molecules in the mixing chamber. The mixing-factor curve does not even reach the values for the angle mixer.

An advantage of the profile measurements lies in the fact that, with a known pressure pattern along the mixing chamber, the profiles can be evaluated as a function of the degree of mixing for any desired nozzle pressure ratio. The temperature and pressure profiles measured in this test were evaluated for the nozzle pressure ratio and flying speed of an aircraft flying at 11-km (36,000 ft) altitude and Mach 0.9 in order to be able to discuss a case of practical interest. The evaluation of the profile measurements at mixing-chamber length = 0 corresponds to the thrust of the bypass engine without mixing. The results obtained for thrust with mixing are referred to this thrust. The values of thrust gain are plotted in Fig. 14 against the ratio mixing-chamber length/mixing-chamber diameter.

The superiority of the chute mixer over the other two mixers investigated becomes even clearer. At a mixing-chamber length of only just over 2 mixing chamber diams the maximum thrust is achieved. After this point the curve falls flatly because the momentum gain due to elimination of the lack of uniformity of the stream is lower than the momentum loss

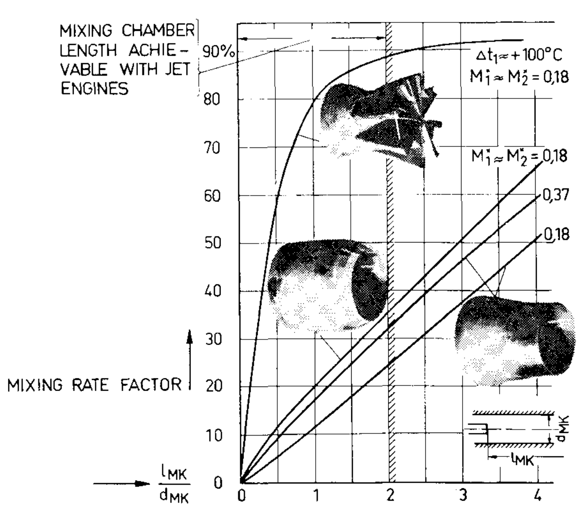

Fig. 13 Mixing factor as a function of mixing-chamber length. The mixing factor indicates how much of the maximum possible exchangeable total energy has actually been transferred.

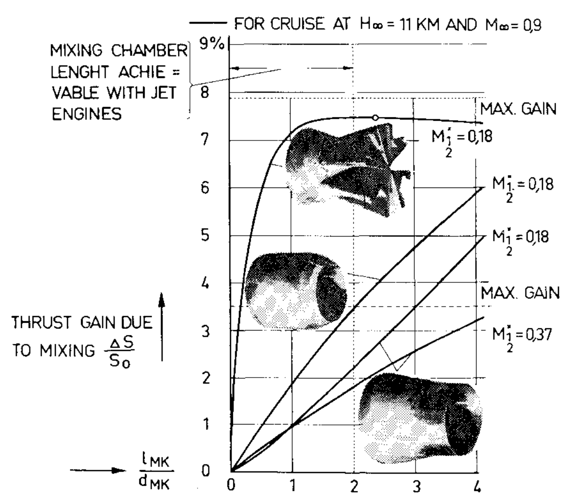

Fig. 14 Thrust gain as a function of the mixing-chamber length for three different mixers and two different mixing-chamber inlet Mach numbers.

due to mixing and in particular due to the friction on the mixing-chamber wall (the higher-energy primary stream, as shown in the polar diagrams of Fig. 12, adheres more and more to the wall as the mixing-chamber length increases). With the chute mixer the maximum thrust gain was achieved at a mixing factor of 91.5% and a mixing-chamber length of 600 mm ($l_{MR}/d_{MR} = 2.34$).

The curve is very flat near the optimum. It is not necessarily worthwhile to try to achieve optimum mixing-chamber length, since even at half the optimum mixing-chamber length the gain is already 90.7% of the theoretical optimum. The other curves did not reach an optimum in the range investigated. By means of a further gasdynamic transfer of energy, the efficiency of the engine can be further improved, provided that the necessary lengths of mixing chamber are available.

The thrust gain measured in the thrust test was 2% for the axial-flow mixer and 3.2% for the chute mixer with a mixing length of just over 1 m.

3.4.3 Comparison of the temperature profiles behind the final nozzle for the axial-flow mixer and the chute mixer

The temperature distribution behind the final nozzle obtained when using the chute mixer differs greatly from that obtained with the axial-flow mixer with the same mixing-chamber length of 4 mixing chamber diams (Fig. 15). The highest temperature measured in the case of the axial-flow mixer is around 500°C, which corresponds to approximately 2.7 times the temperature that would be obtained with perfect mixing. The mixing factor that was determined when the chute mixer was used is 96%; the temperature scatter, as the diagram shows, is very slight, and the final nozzle outlet temperature corresponds in the main to the mixing end temperature of 207°C. This result indicates the advantage of a high degree of mixing within the engine with regard to ground erosion and recirculation.

3.5 Summary

The tests have confirmed the theoretical results for a bypass ratio of $z = 3.2$. A thrust gain was achieved with equal total pressures in the primary and secondary streams before mixing for mixing-chamber inlet Mach numbers equal to and below 0.37. The tests also yielded the interesting result that if a suitable device is used for accelerating the mixing process, mixing factors of over 80%, and hence the main portion of the thrust gain, are obtained with very short mixing chambers.

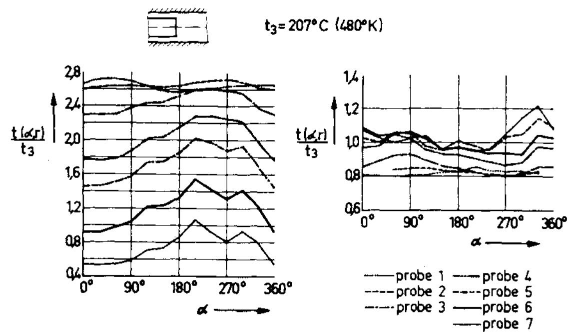

Fig. 15 Temperature distribution beyond the final nozzle.

Mixing systems have many possible applications in aircraft propulsion gas turbines; in addition to the aspects of mixing in the case of combustion chambers, after burners, and bypass engines, the use of ejectors for thrust augmentation by means of jet mixing in VTOL aircraft is gaining importance. The great advantage of flow mixing in aeroturboengines compared with the small expense gives the mixed-flow turboengine many applications in the future, especially in the field of lift engines, a new type of aeroengine. It is worthwhile to study the different possibilities; there is a great amount of interesting work to do.

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