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AERODYNAMIC FIELD PREDICTION BY A STREAMLINE METHOD IN THE EJECTOR SYSTEM OF A PASSIVE INFRARED SUPPRESSOR

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Summary

Reported herein are some of theoretical and experimental activities held by PIAGGIO in the aerodynamic field prediction inside an ejector system which his IR suppressor concept is based on.
This report summarizes the study on both the analytical model and the computer code development joined to some correlations to experimental results on typical ejector systems representing a scaled down IR suppressor designed for a defined gas turbine engine.
A previous paper was written showing PIAGGIO activity to simulate the aerothermodynamic phenomena through mathematical models. This paper now is but referring to a specific area of simulation that is the complex aerodynamic field inside an IR suppressor where two flows are mixing together.
The diffusion process of thermodynamical and mechanical quantities has been simulated by a method that can be fitted on the classical streamline schemes and is based on influence matrices under well defined boundary conditions.
This method appears rather flexible to describe a wide class of ejector systems.
A wide trade-off study is shown for both theoretical and experimental results and also some information inferred from literature are accounted for.
The experimental results have been used to test the mathematical model and satisfactory agreement has been obtained.

1. INTRODUCTION

The infrared technology of heat seeking missile requires more efficient IR signature suppression for helicopters. The improvements on heat seeking detectors have mandated the requirement for an efficient hot metal and plume radiation suppression. Lower helicopter target signatures are required to enable probable escape from detection when operating in hostile zones.

Other devices addressing the radiation sources such flare dispensers and jammers are in general unactractively large and heavy so they adversely impact the helicopter mission performance.

The importance of a defense against weapons locking on the hot end of an engine has been recognized and an engagement to develop suitable technology and hardware has been made.

PIAGGIO has conceived and has under development an IR suppressor for a gas turbine helicopter engine in house manufactured.

A dedicated effort is made to improve the efficiency of the IR suppressor addressing both the engine hot metal and the exhaust plume radiant emissions that are the most important radiant sources in the helicopter. (see Fig. 1-1)

Studies predicted that these emissions can be satisfactorily lowered by diluting the exhaust gas and film cooling the hot metal walls.

This requires a device able to pump ambient air to achieve these tasks but inducing low power penalties to the engine. Reduced weight and size are also important constraints. The shape itself must be able to hide the hottest parts of the engine exhaust nozzles from an afterend lock-on.
The concept envisaged by PIAGGIO is a tail pipe two-stage ejector to dilute the hot exhaust plume and to cool the hot visible walls. No moving parts are foreseen and the characteristics of mechanical integrity are enhanced. Lightness, small size and a self contained philosophy are joined to features of mechanical simplicity.
(See fig.1-2)

To deeply analyse the ejector aero-thermo performance many analytical models have been studied and translated in some computer programmes.

This software has been proven to be an excellent tool to design ejectors or to verify experimental results on test models.

It is evident that a well defined method of design will involve the knowledge of the two main parameters: the signature level and the allowable engine power penalty which have to be achieved.

Trade-off studies on both ejector and engine performance are an easy matter only by a computerized way.

The heart of this design activity are the cross-correlation studies between the ejector inner aerodynamic field and the heat transfer phenomena in two fluids mixing together.

The optimization of the aerodynamic parameters is strictly function of temperature requirements on both plume and walls.

Unfortunately poor data are available from literature on this subject so PIAGGIO developed an aerodynamic model based on a streamline method with the aim to predict the aerodynamic field and mixing rate in an ejector system. Sets of data required for heat transfer calculation on both plume and walls emissions are produced.

2. ANALYTICAL MODEL

A number of methods exist for the calculation of a steady plane flow through a channel of a given shape with defined boundary conditions.
Not so many reports on the mixing flow due to a primary hot jet entraining

into the channel a secondary stream of cold air, as required for the dilution process to take place, can be found.

Even if the problem of the turbulent diffusion of transport properties has been extensively studied from a physical point of view /1/ and a lot of experimental tests have been made in different conditions, the need of a general computation code, able to assist the IR suppressor ejector design, was felt.

Instead of developing an analytical model accounting for the flow features in a rigorous physical way, it was preferred to choose a more flexible model based on a suitable simulation of the diffussion process, whose agreement to the actual flow could be obtained by calibration with experimental results, derived both from the literature and from tests performed at PIAGGIO facilities.

The basic idea was to fit the well-known streamline curvature computing procedure with a mixing model based on the cross-influence of adjacent streamlines with regard to some transport properties.

The streamline curvature method for the calculation of a steady plane or axisymmetric inviscid flow is well-known, and only the main equations to be solved are reported here for convenience of introducing the diffusion model.

As far as the boundary layer is concerned, the classical methods of calculation do not seem applicable to the case of a louvered wall. Waiting for an extensive experimental enquiry to be performed in PIAGGIO facilities, the boundary layer effects have not been included in the present analytical model.

Considering first a plane curved channel, the Euler equation is written along directions that are quasi-orthogonal (q.o.) to the bulk flow (see fig. 2-1).

The final form of the equation here used is:

$$c\left(\frac{dc}{d\psi}\right)_{\varepsilon}=\frac{\cos\sigma}{\varrho c l}\left[c\left(\frac{dc}{dx}\right)_{\psi}\mathrm{tg}\,(\alpha+\sigma)+c^{2}\left(\frac{d\sigma}{dx}\right)_{\psi}\right]+\left(T_t-T\right)\left(\frac{ds}{d\psi}\right)_{\varepsilon}+\frac{1}{\varrho_t}\left(\frac{dp_t}{d\psi}\right)_{\varepsilon}. \tag{1}$$

The continuity equation to be satisfied is:

$$m=\int_{q_{ps}}^{q_{ss}} c\left(\cos\sigma\,\cos\alpha-\sin\sigma\,\sin\alpha\right)\varrho l\,dq. \tag{2}$$

It is worthwhile to note that the channel width could be different for different q.o., so allowing, within an acceptable approximation, the treatment of a tapered channel with a plane model.

Referring to an axisymmetric case (fig. 2-2), with no tangential velocity components, the two main equations are:

$$c\left(\frac{dc}{d\psi}\right)_{\varepsilon}=\frac{\cos\sigma}{2c\varrho r\pi}\left[c\left(\frac{dc}{dx}\right)_{\psi}\mathrm{tg}\left(\alpha+\sigma\right)+c^{2}\left(\frac{d\sigma}{dx}\right)_{\psi}\right]+\left(T_t-T\right)\left(\frac{ds}{d\psi}\right)_{\varepsilon}+\frac{1}{\varrho_t}\left(\frac{dp_t}{d\psi}\right)_{\varepsilon}. \tag{3}$$

$$m=\int_{0}^{R} 2c\left(\cos\sigma-\sin\sigma\,\mathrm{tg}\alpha\right)\varrho r\,dr. \tag{4}$$

In this case the symmetry condition applied for r=0 gives:

$$\left(\frac{dc}{d\psi}\right)_{r=0}=0 \tag{5}$$

so overcoming the discontinuity otherwise appearing in eq. (3).

When the inlet flow exhibits large non-uniformities, a mixing process taes place, with the main consequence f a spreading across the channel of he flow properties.

he mixing process as basic phenomenon s due to some turbulence level, which s responsible of a lateral transport f physical quantities. Within a turulence characteristic length, the low cannot be considered (and it is ot indeed) steady, so the above equaions are not longer valid, neither treamlines exist in a true sense.

evertheless, limiting the detail leel of the analysis to a length scale reater than the characteristic mixing engths, a mixing flow can be yet tudied as a steady one, providing an lgorithm able to give the istribution of total pressure and nthalpy determined by the mixing rocess itself.

his algorithm should match the folloing requirements:

) to give for each q.o. inside the channel, the distribution of: $p_t(\psi), h_t(\psi)$, which the partial derivatives

$$\frac{\partial p_t}{\partial \psi} \ , \ \frac{\partial s}{\partial \psi}$$

in (1) or (3) are depending on;

) to be compatible with the energy conservation law and with an assumed total pressure loss along the flow;

) to be enough flexible to be calibrated with reference to experimental data and to fit within the general calculation framework.

nce the total pressure and enthalpy istributions have been defined the ntropy can easily be obtained from:

$$\frac{\partial s}{\partial \psi} = \frac{1}{T_t}\left[\frac{\partial h_t}{\partial \psi} - \frac{1}{\varrho_t}\frac{\partial p_t}{\partial \psi}\right] \qquad (6)$$

or a general quantity g the distribuion at the k-th q.o. is obtained from he previous one applying an influence atrix $|a_{ij}|$ whose terms denote the influence at the i-th streamline of the value at the j-th streamline

$$g_{k,i} = \frac{1}{N}\sum_j a_{ij} g_{k-1,j} . \qquad (7)$$

The normalizing factor N is choosen as follows:

a) as far as h_t is concerned, the energy conservation gives N by:

$$\int_0^m h_{t_k} d\psi = \int_0^m h_{t_{k-1}} d\psi \qquad (8)$$

b) as far as p_t is concerned, once (6) has been integrated, the entropy increment is checked against the total pressure loss $\Delta p_t/p_t$:

$$\int_0^m s_k d\psi - \int_0^m s_{k-1} d\psi = m \mathcal{R} \frac{\Delta p_t}{p_t} . \qquad (9)$$

For each q.o. the influence matrix $|a_{ij}|$ is evaluated taking into account the distance between the i-th and j-th streamline and the distance between the previous q.o.

3. COMPUTER CODE

The previous algorithm has been coded in a suitable computer program.

Besides the channel geometry, the inputs are:
- the primary and secondary mass flow rate;
- the static pressure in the mixing inlet plane, assumed uniform as customary;
- the temperatures of the primary and secondary flow;
- the total pressure loss distribution.

The result is the flow description in the whole channel. Because the code is not yet implemented with the analysis of recirculation zones their appearance is simply detected and monitored.

Among the results obtained, particular interest for the IR suppressor performance prediction have the following:
- the temperature distributions along the channel walls and across the exhaust flow;
- the static pressure distribution along the walls.

These results permit the evaluation of:
- the plume temperature level and the effectiveness of the desired dilution;
- the wall suction capability of the ejector, for the calculation of the film cooling performance.

The influence of film cooling flow can be considered by mixing it with the bulk flow, so iterations are necessary to take into account the wall pressure variations due to the increased mass flow rate along the channel.

Moreover the computer code is based on specialized routines that perform:
- the solution of the main equations, with the streamline curvature method;
- the simulation of the mixing processes;
- the calculation of the gas properties.

Computing time on IBM 4341 computer is of the order of a few seconds per iteration in the streamline curvature procedure, while the total time depends on the desired accuracy and on the channel geometry. In the worst case of highly curved channels, a fifty iterations run is necessary to meet a relative error below 0.001.

A good performance in this respect has been obtained by the use of dynamic damping factors as suggested in /2/.

4. TEST CASES

The computer code has been tested on a wide number of cases for calibration purposes. Three different situations are shown here.

a) Planar free jet
   For this case the experimental reference is the reference /3/.
   The results are shown in fig. 4-1 where the axial velocity decay is plotted along the jet axis. In this case the model appears to be sensitive to the axial spacing of the calculation stations, and moreover an exact modelling of the actual experimental situation becomes impossible because an external channel wall is necessary even if placed far apart.

b) Axisymmetric jet
   Reference made to the experimental values reported in /4/, /5/, both the center line velocity and temperature decay has been calculated in two different cases. Fig. 4-2 shows the theoretical results compared with those reported in /4/, and fig. 4-3 with those reported in /5/. The calculated decay of temperature results steeper than that of the velocity in agreement with the referenced experimental data; however the axial position of the calculated curves should have been displaced somehow downstream (temperature) or upstream (velocity). This fact follows from the known difficulty to treat with the same model the potential core region and the mixing region.
   Indeed the present model can do it with a proper different spacing of the q.o. in the two zones.

c) Curved ejector
   The flow field obtained in this case has been compared with the experimental results obtained at PIAGGIO facilities on suppressor scaled-down models.
   In the case of fig. 4-4 a ram pressure has been simulated in the experimental facility, and the velocity ratio between the secondary and primary flow c_s/c_p at the inlet was around 0.5, that ensures a quite stable operation of the ejector. The agreement between calculated and measured values is fa-

irly good and the suction capability of the system is enhanced.
In the case of fig. 4-5, the actual (test) velocity ratio c_s/c_p is around 0.17.The same figure in the analytical model creates unstable operation as indicated by the appearance of recirculation zones. Additional calculations have been performed modifying the inlet area ratio in order to obtain a velocity ratio of about 0.5. This means to suppose the mixing to start some q.o. dowstream.
The agreement with the experimental results is less satisfactory than the planar and axisymmetric cases.
Fig. 4-6 and fig. 4-7 show the suction pressure trends along the pressure surface both in the same boundary conditions as before: ram effect and static.
Also on this side of the channel, the ram effect seems to offer a more stable operation as regards the suction effect whereas a static condition appears less favourable to stabilize the pressure field along the wall. The experimental results showed indeed some tendency of the primary hot jet to impinge the wall at the middle of the channel.
In fig. 4-8 and fig. 4-9 the temperature distributions on the streamlines nearest the walls of the curved ejector are shown for the previous two conditions: ram and static. The good agreement between the simulation and the test is evident.
However, other PIAGGIO computer programmes are devoted to the task of predicting the wall temperatures with more accuracy.
In fig. 4-10 a typical streamline pattern is shown as plotted by the computer code.

CONCLUDING REMARKS

eral comments can be drawn from the parison activity that has been permed and reported above for a few ca-
;
the model is quite flexible, and can be adapted to different experimental situations;
b) as far as curved ejectors are concerned, additional experimental data are required for a more accurate calibration;
c) the analytical model is satisfactorily reliable and is a good support for the analysis of the complex inner aerodynamic field of a multistage ejector system.

6. FUTURE DEVELOPMENTS

PIAGGIO activity in the field of IR suppressors is oriented towards a differentiation of basic layouts and arrangements, based on the specific applications.

As a consequence, the above computer code will be improved to properly handle:
a) general mixing loss correlations, for different geometrical shape of ejectors;
b) the recirculation zones, that could exist in the flow rate ranges typical of IR suppresssor ejectors;
c) the film cooling properties of various louvered walls, including their heat transfer coefficients.
d) the impingement effect of the primary hot jet onto the pressure surface of curved ducts.

7. ACKNOWLEDGEMENTS

The writers wish to thank Mr. Massone and Mr. Mordeglia of the aero-thermo and structural R & D team whose contribution made possible to perform the work herein reported.

8. REFERENCES

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9. LIST OF SYMBOLS

Symbols

a	element of the influence matrix
c	flow velocity
D	diameter of primary jet nozzle
g	general quantity
h	enthalpy
l	channel width
m	mass flow rate
N	normalizing factor
p	pressure
q	coordinate along q.o.'s
r	radial coordinate
R	radius
$\mathcal{R}$	gas constant
s	entropy
T	absolute temperature
x	x-axis coordinate
y	y-axis coordinate
α	q.o. tilt angle from y direction
ε	coordinate normal to q.o.'s
ϱ	density
σ	streamline slope
ψ	stream function

Subscripts

c	centerline
i	i-th row of a matrix
j	j-th column of a matrix
k	k-th q.o.
t	total
p	primary
ps	pressure side
s	secondary
ss	suction side

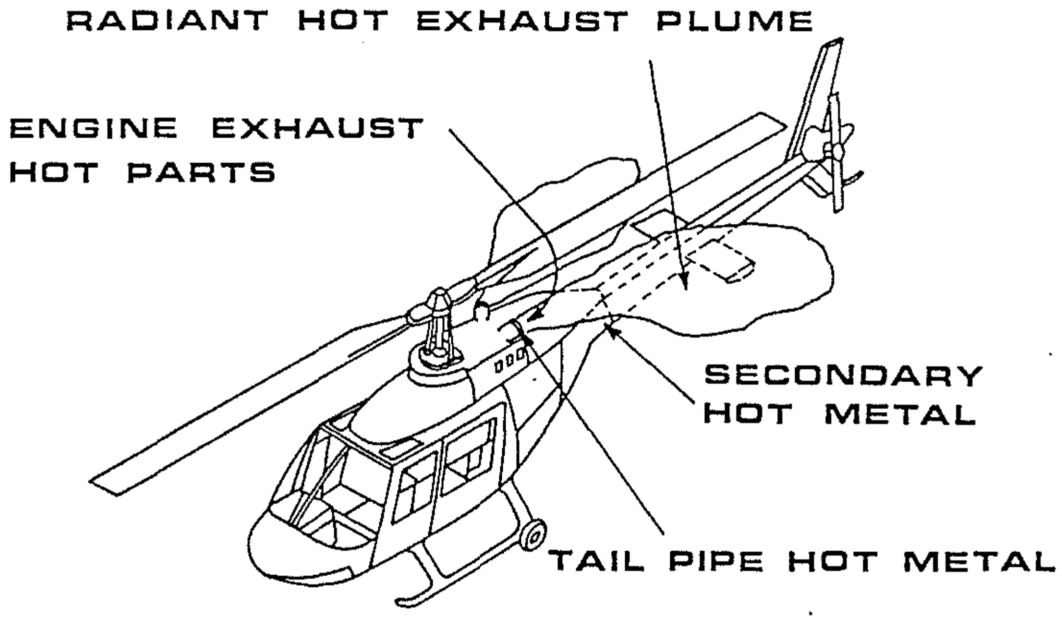

FIG. 1-1 TYPICAL RADIANT IR SOURCES

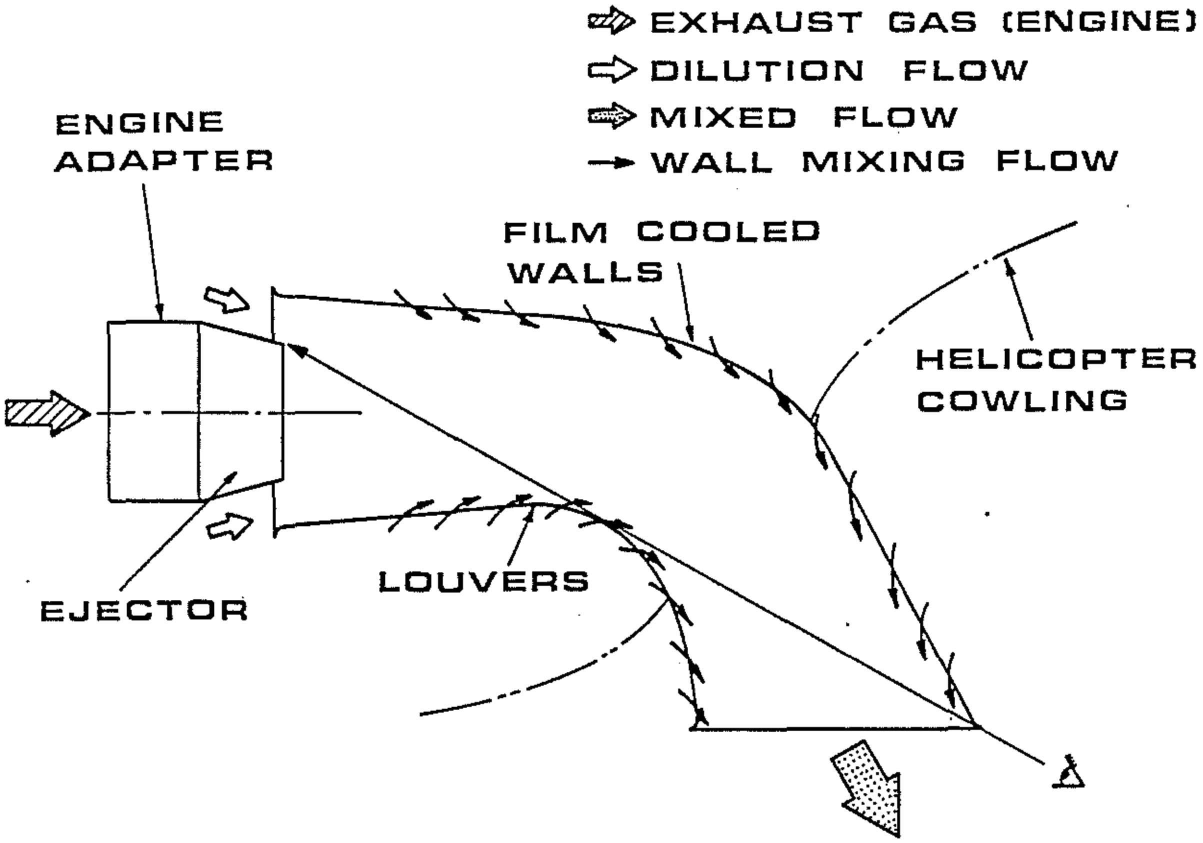

FIG. 1-2 IR SUPPRESSOR BASE CONCEPT

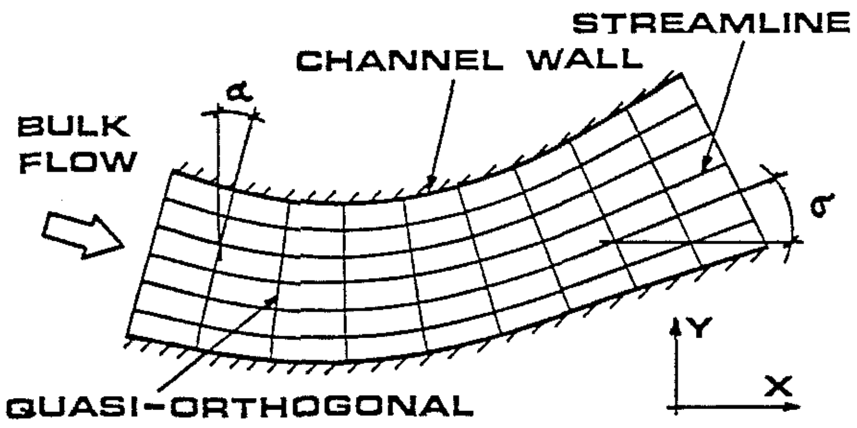

FIG. 2-1 STREAMLINE METHOD
PLANE CHANNEL

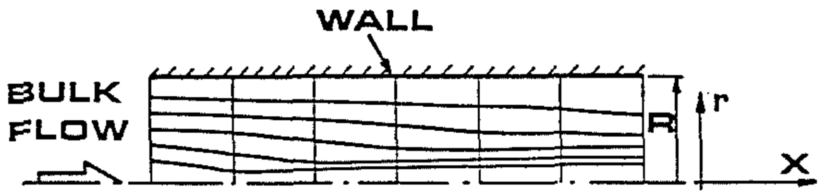

FIG. 2-2 STREAMLINE METHOD
AXISYMMETRIC CHANNEL

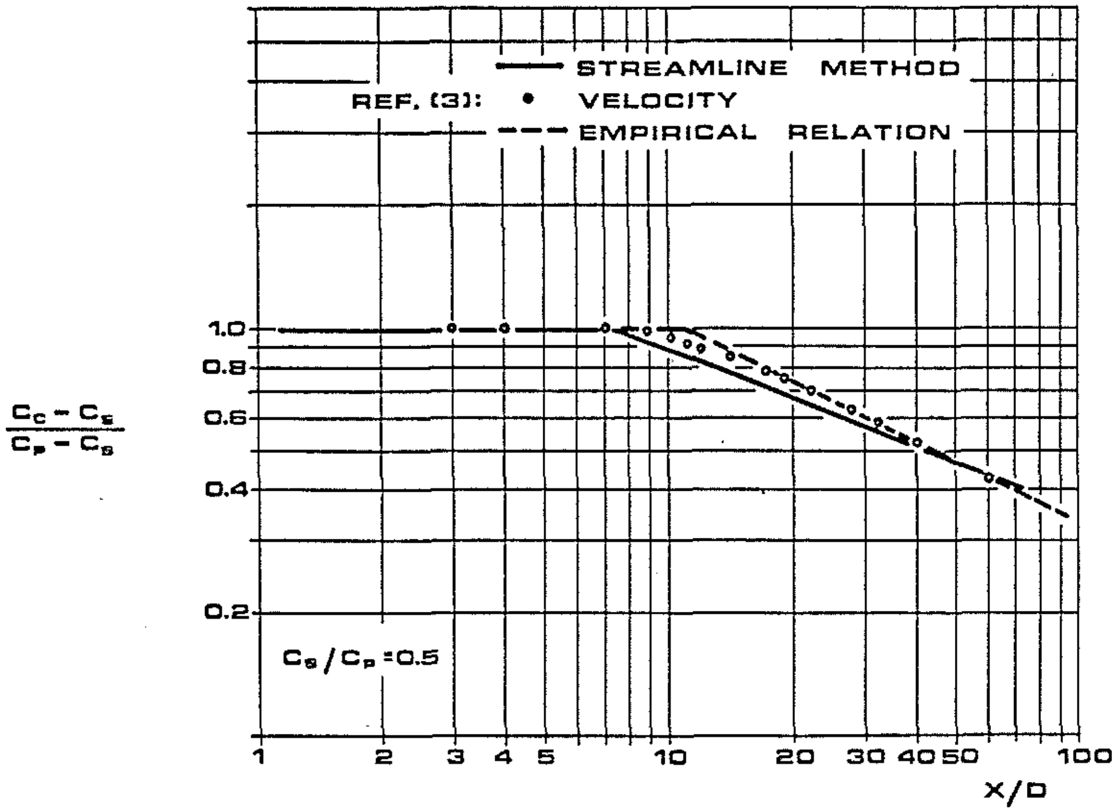

FIG. 4-1 PLANAR JET: CENTER-LINE
VALUES OF VELOCITY

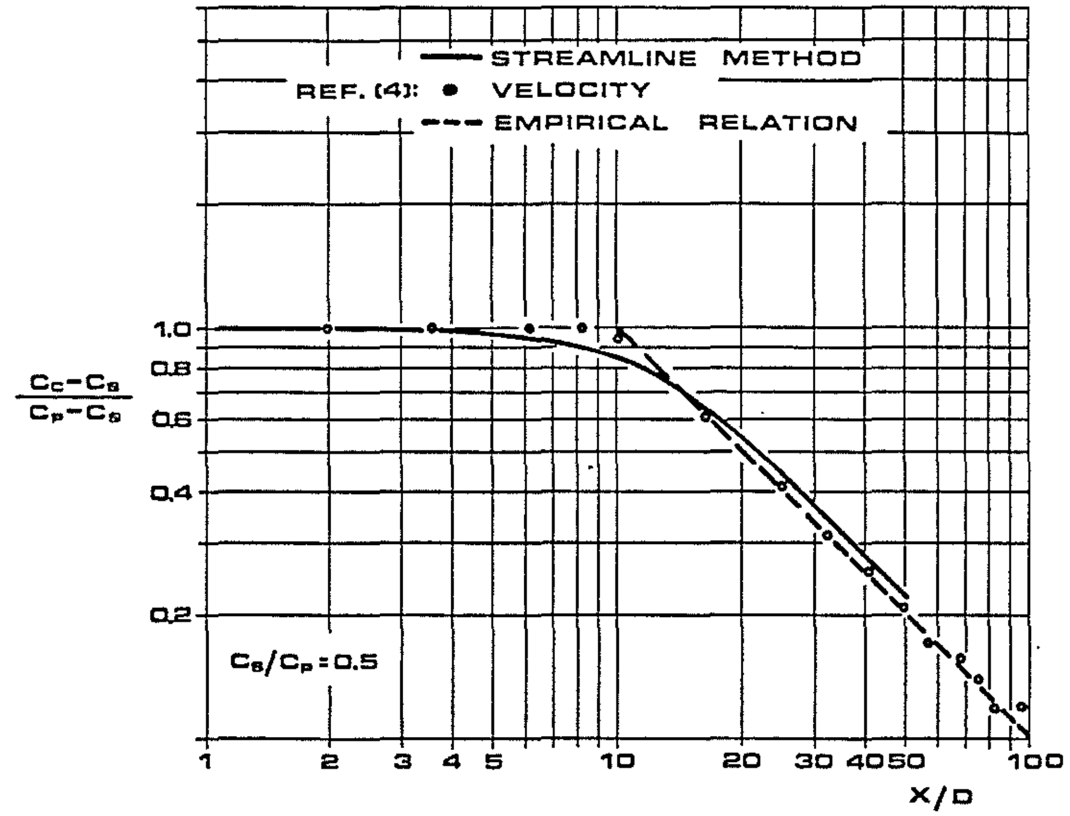

FIG. 4-2 AXISYMMETRIC JET: CENTER-LINE VALUES OF VELOCITY

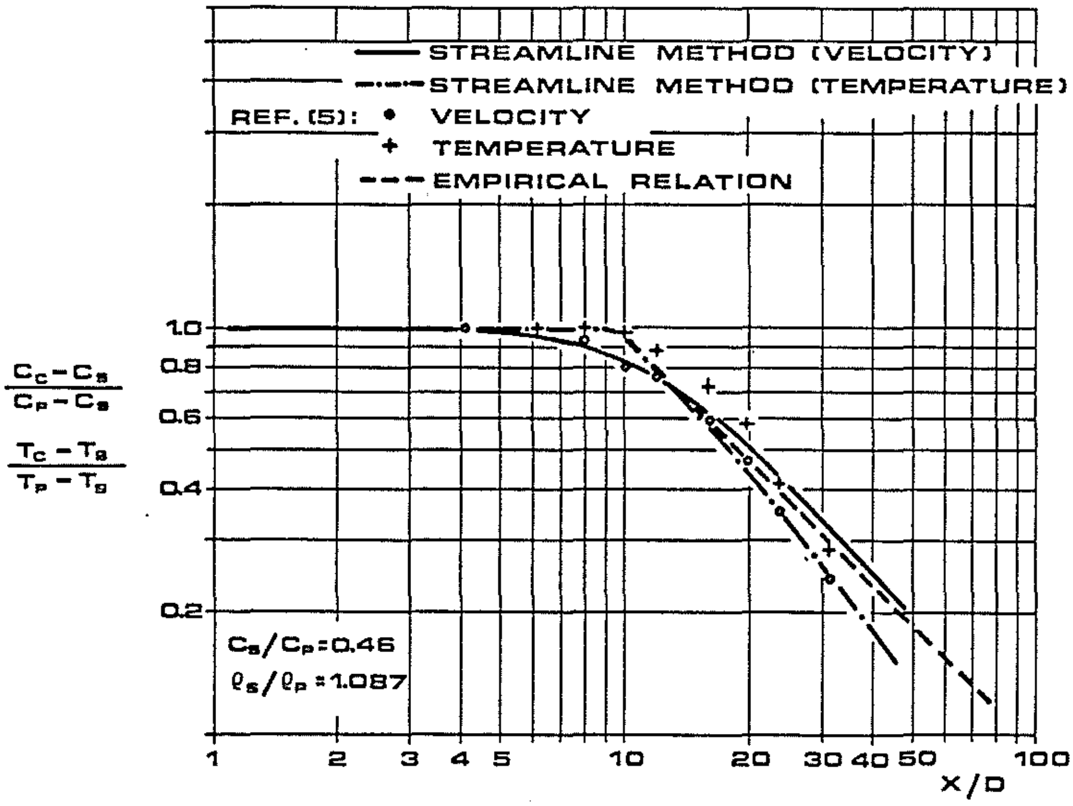

FIG. 4-3 AXISYMMETRIC JET: CENTER-LINE VALUES OF VELOCITY AND TEMPERATURE

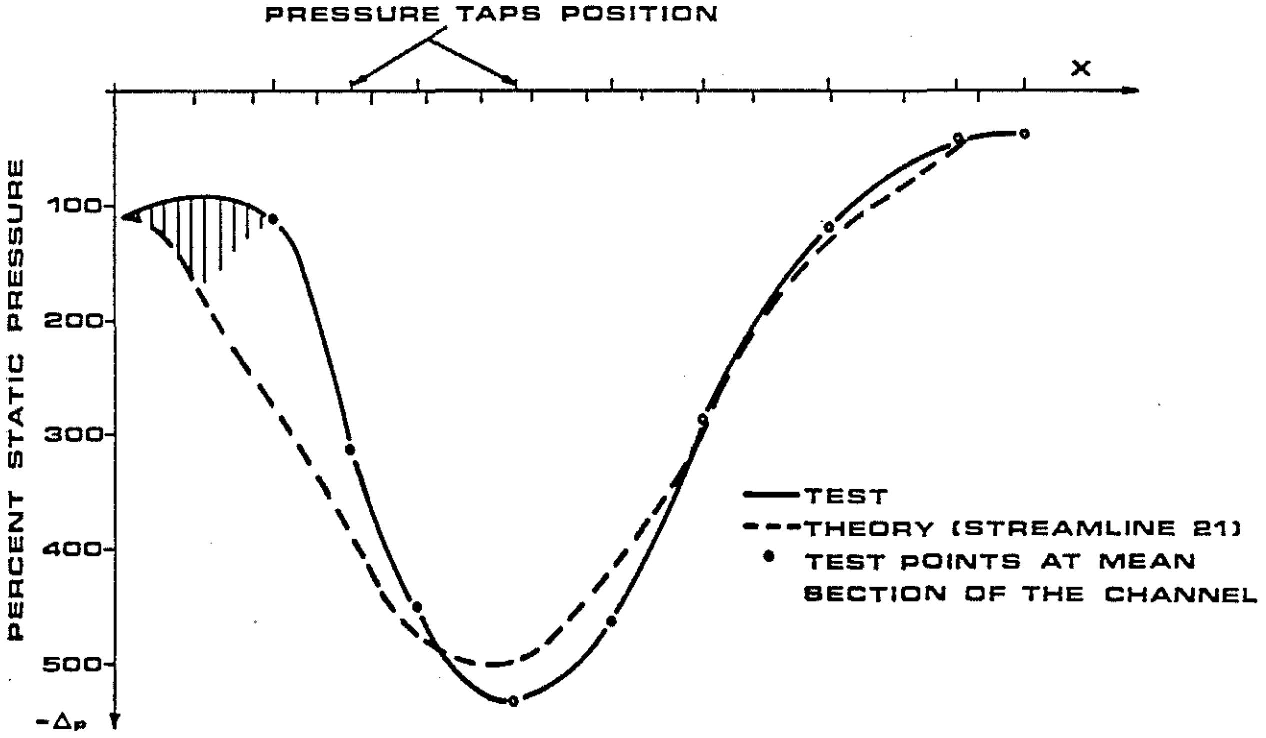

FIG. 4-4 TYPICAL AERODYNAMIC FIELD ON SUCTION SURFACE IN SIR MODELS (RAM EFFECT)

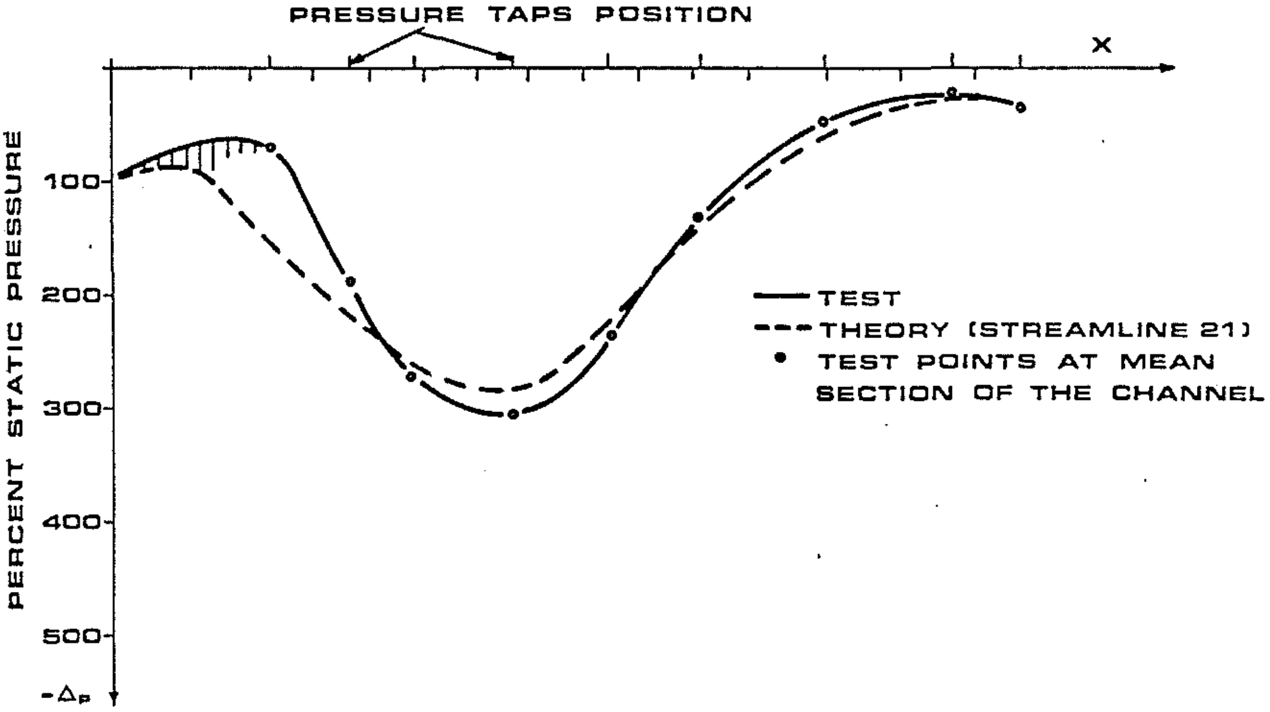

FIG. 4-5 TYPICAL AERODYNAMIC FIELD ON SUCTION SURFACE IN SIR MODELS

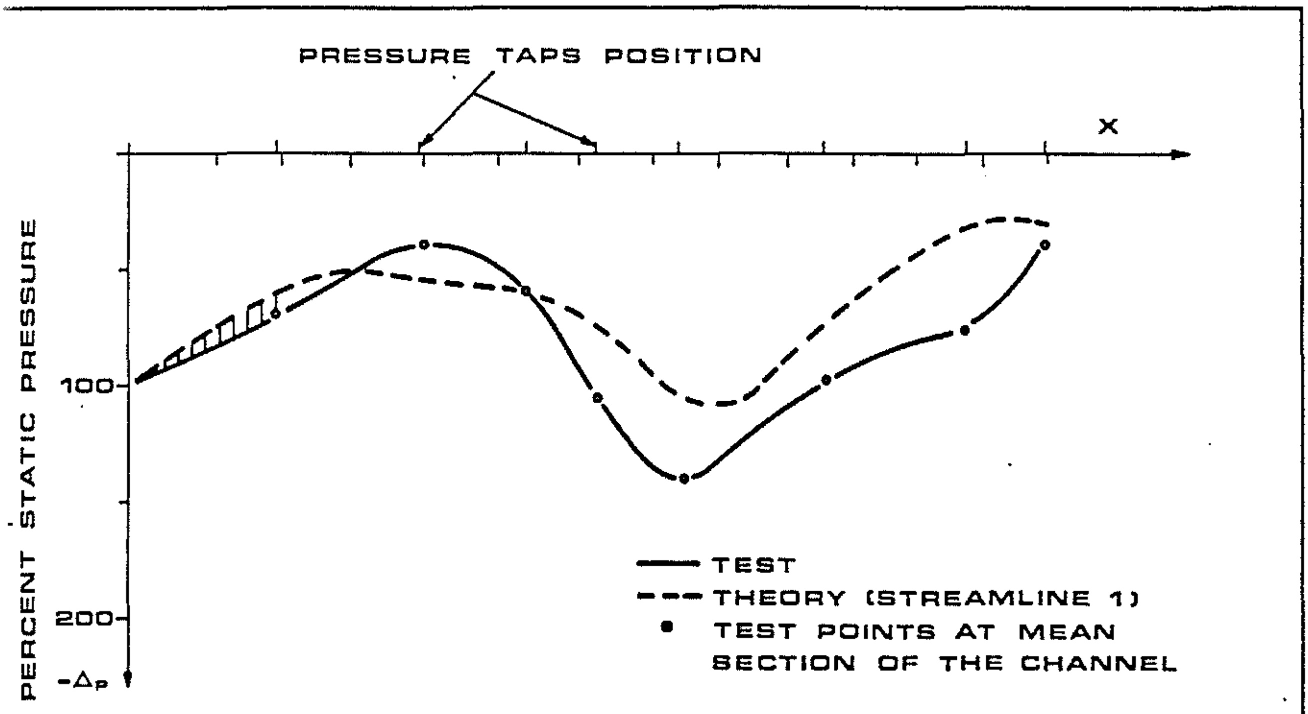

FIG. 4-6 TYPICAL AERODYNAMIC FIELD ON PRESSURE SURFACE IN SIR MODELS (RAM EFFECT)

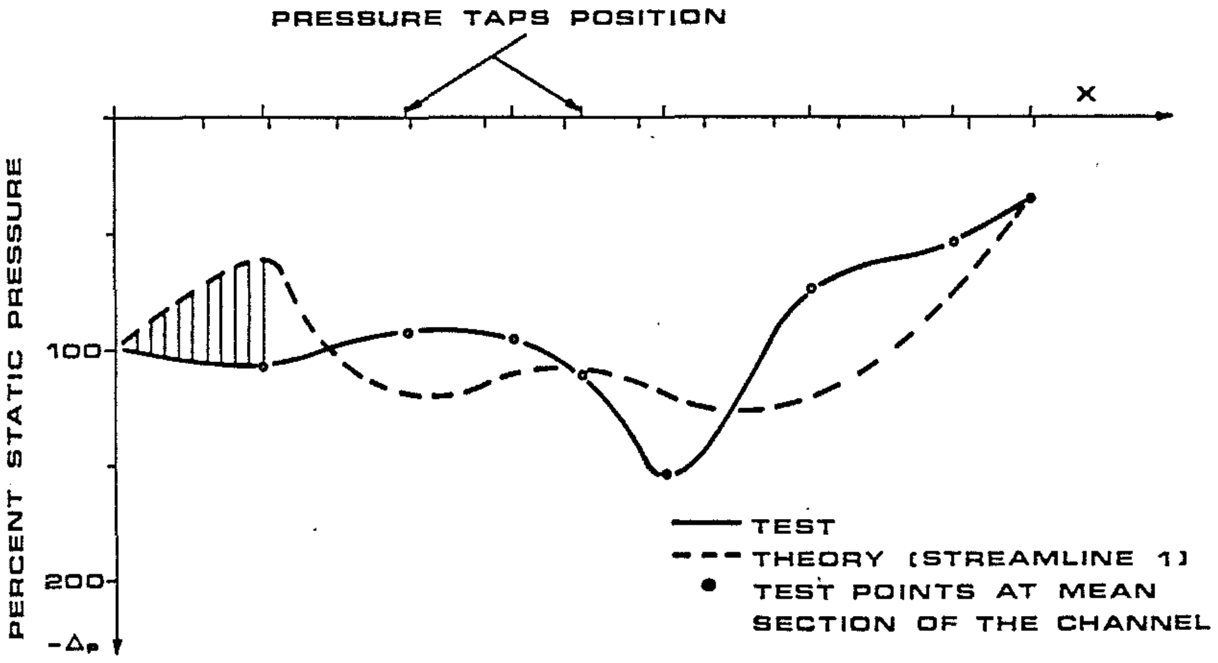

FIG. 4-7 TYPICAL AERODYNAMIC FIELD ON PRESSURE SURFACE IN SIR MODELS

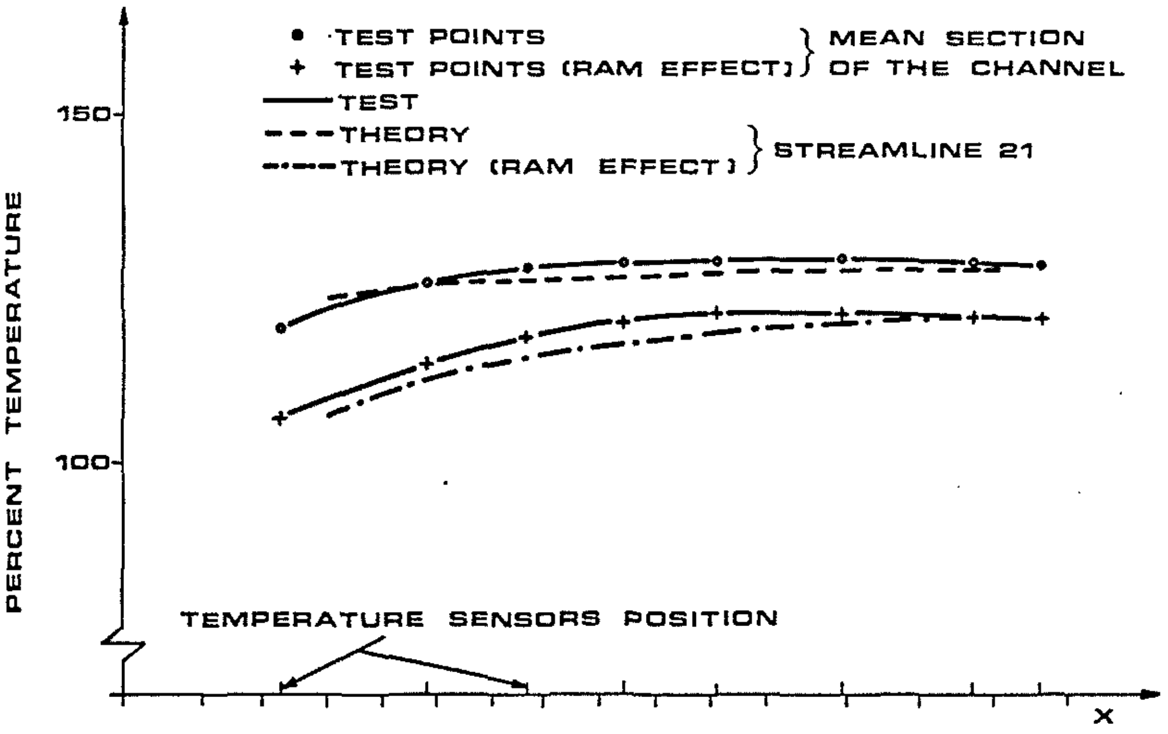

FIG. 4-8 TYPICAL TEMPERATURE DISTRIBUTION ON SUCTION SURFACE OF SIR MODELS

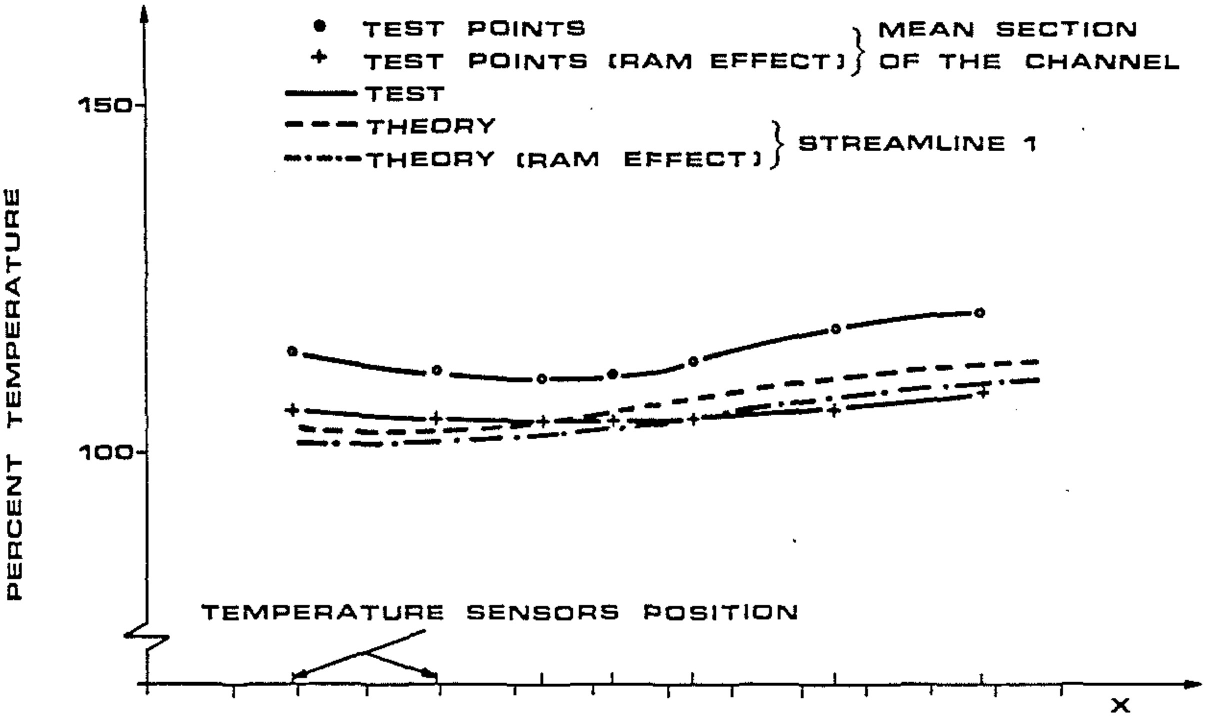

FIG. 4-9 TYPICAL TEMPERATURE DISTRIBUTION ON PRESSURE SURFACE OF SIR MODELS

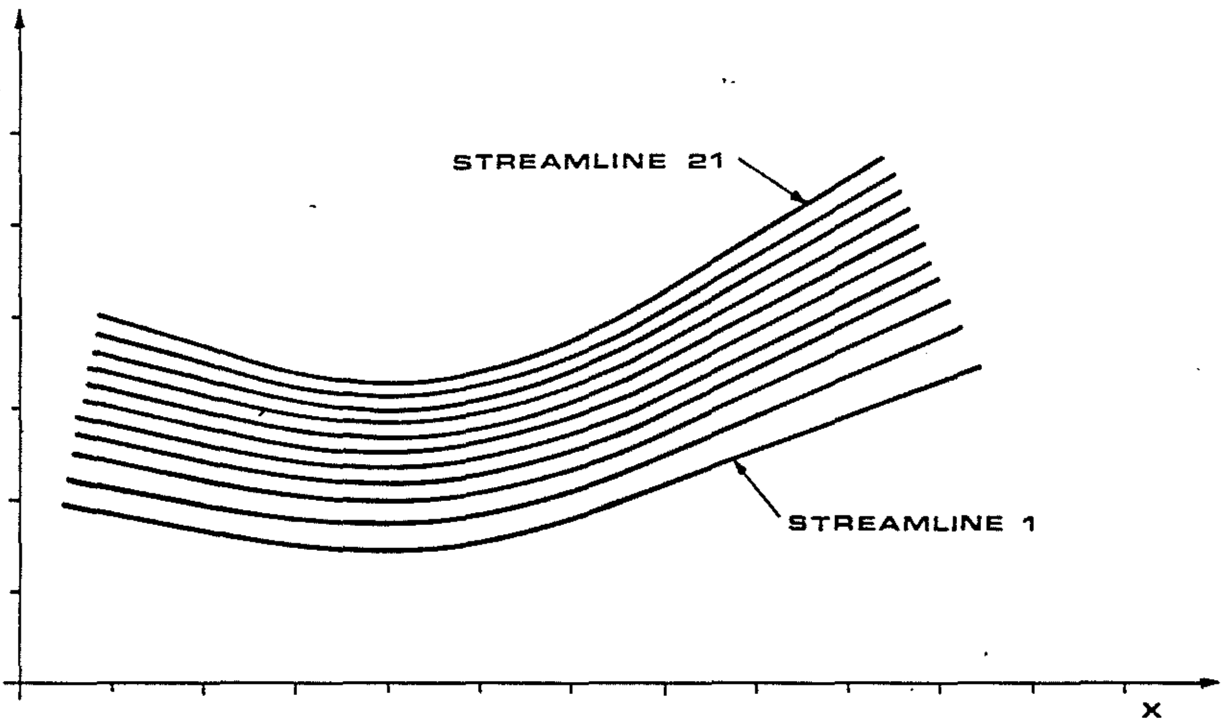

FIG. 4-10 TYPICAL STREAMLINE PATTERN IN SIR MODELS