THE BEHAVIOUR OF AIR FLOW THROUGH DIFFERENT NOZZLE PROFLIES

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ABSTRACT

This work involved the study of air flow through different types of nozzles. The studies include the assessments and determination of the conditions at throat, including the critical pressures, the mass flow rates and the critical velocities together with the condition at nozzle entry (subsonic) and nozzle exit (supersonic). The stagnation conditions were also discussed and assessed.

The studies include also, the experimental assessment of the effect of wide angle divergence, the determination of critical pressure ratio by varying the mass flow rate and the exit pressures.

The analysis carried out during this study was restricted to one dimensional flow, where the velocities and properties of air were assumed to change only in the direction of the flow and that air velocities was assumed to be constant at a mean value across the cross-section of the nozzle.

ملخص:

في هذه الورقة تمت دراسة تدفق الهواء في عدد من الفونيات. اشتملت الدراسة على تحديد وتقييم حالات الضغط الحرج، كتلة ومعدل الهواء المتدفق والسرعات الحرجة عند عنق الفونية مع الأخذ في الاعتبار أن السرعات عند مدخل الفونية تحت الصوتية وعند مخرج الفونية فوق الصوتية، كما تم أيضاً في هذه الدراسة دراسة حالة الركود.

هذه الدراسة اشتملت أيضاً على دراسة تأثير زاوية الانفراج وذلك بتحديد نسبة الضغط الحرج بتغيير معدل التدفق وضغط الخرج.

التحليل في هذه الدراسة تم في اتجاه بعدي واحد والذي فيه اعتبرت السرعات وخواص الهواء تتغير فقط في اتجاه التدفق وسرعات الهواء اعتبرت ثابتة عند قيمة متوسطة في وسط مقطع الفونية.

1. INTRODUCTION

The steady flow energy equation, deduced as the first law of thermodynamics, relates the heat and work transfers across the boundary of an open system to the mechanical and thermodynamics properties of the fluid at inlet and outlet, assuming them to be constant across the cross-section of the flow.

Applying this equation to the adiabatic flow in a nozzle, with previous knowledge of initial enthalpy, initial velocity and final enthalpy, enables the final velocity to be calculated. Before this is applied, an assumption is made for the stagnation properties of the fluid flow.

The nozzle, which is a device (an open-system) used for the purpose of guiding the expansion of a substance to the state where the kinetic energy of the substance is relatively large, is a duct of smoothly varying cross-sectional area in which steadily flowing fluid can be made to accelerate in the duct by a pressure drop along the duct. If the fluid is made to decelerate in the duct causing a pressure rise along the stream, then the duct is called a diffuser. The two main types of nozzles are:

1) Convergent
2) Convergent-divergent.

There are so many practical applications which require a high velocity-stream of fluid, like steam and gas turbines, where nozzles are used to satisfy the above demands. The manner in which work originates in a gas or vapour turbine is, first, the expansible fluid expands through a nozzle, during which process some of the fluid initial energy is converted into kinetic energy; then the issuing jet of high velocity fluid passes across the turbine blades which have been designed to change the momentum of the stream. The consequence of the change of momentum is a force which does work (turning the turbine shaft).

With the advent of high-speed flight, turbine jet engines, ram jets and rockets, fluid dynamics has progressed and been enormously extended, particularly the branch dealing with compressible flow or gas dynamics. This makes the use of nozzles as a means of propulsion, a very important aspect in this growing field. Since the fluid flowing through the nozzle is accelerated relative to the nozzle, then by Newton's Third Law of motion, it follows that the fluid exerts a thrust on the nozzle in the opposite direction to the fluid flow.

In the jet aero plane and the ram-jet, the atmospheric air is drawn in, compressed, heated and allowed to expand through the nozzle, leaving the aero plane at high velocity; the rate of change of momentum of the air backwards relative to the aircraft gives a reactive force or thrust to the aircraft. All propulsion engines consist of one or more of three components; a diffuser, source of energy and a propelling nozzle. In turbine-jet engines, the energy source comprises a compressor, a combustion chamber and turbine. In this case no network is produced by the turbine, but part of the energy available in the expanding gases leaving the nozzle is used for developing thrust.

In order to achieve propelled flight in the space, where there is no atmospheric air to be drawn into the space vehicle, it is necessary to carry both the fuel and its oxidant. This is known as rocket propulsion.

2. PREVIOUS WORK ON NOZZLES

Supersonic aircraft required convergent-divergent nozzles for optimum performance at high Mach number and large nozzle pressure ratio (Total/ambient). Sometimes it is necessary to operate such a nozzle at low pressure ratios with the accompany possibility of flow separation. The next exact nature of the separation i.e., whether it is stable or not, could affect an aircraft control characteristics [1] in which a test programmed was performed using 1:2 area ratio scale model nozzle to determine the nature of the flow field, secondary flow of 0 and 2% were introduced into the nozzle, from which the following results were obtained:

High response pressure transducer readings internally along the nozzle lip provide no indication of a moving shock either axially or circumferentially. Pressure fluctuations were greater near the point of separation. The maximum amplitude was small, 3.5% of the total pressure.

It was shown that the velocity at the throat of nozzle operating at its design pressure ratio, it's the velocity of sound at throat conditions. The flow up to the throat is subsonic and after the throat is supersonic. In the same way it was shown that for a nozzle that is convergent only, the fluid will attain sonic velocity at exit if the pressure drop across the nozzle is large enough. The ratio of the pressure at the section where sonic velocity is attained to the inlet pressure of the nozzle is called the critical ratio.

The jet propulsion engine study was briefly involved and discussed by Roger and Mayhew [2]. The two distinct classes of propulsion engine are those which make use of atmospheric air as main propulsive fluid and those which carry their own propulsive fluid e.g. (rocket motors) was also discussed. The economical use of the nozzle was investigated and discussed by Brown and Hamilton [3,4]

3. KINETIC ENERGY-ENTHALPY RATIO RELATIONSHIP

When air, gas and vapour expands through a nozzle, part of its heat energy content is converted into kinetic energy at the nozzle exit and, in this form may then do work, e.g. on the blades of a turbine.

In the analysis which follows, the effects of friction and heat transfer will be ignored and the flow considered to isentropic.

From the steady flow energy equation of air or gas we have

$$gz_1 + U_1 + P_1V_1 + \frac{v_1^{\,2}}{2x10^3} + Q = gz_2 + U_2 + P_2V_2 + \frac{v_2^{\,2}}{2x10^3} + W$$

$$= \quad = \quad + \quad =$$

$$h_1 + \frac{v^2{}_1}{2x10^3} = {}_2 + \frac{{}^2{}_2}{2x103}$$

$$\frac{v_2^{\,2} - v_1^{\,2}}{2x10^3} = {}_1 - {}_2 \text{.................................(1)}$$

If the approach velocity v_1 is negligible, i.e. expanding form a large vessel [5,6].

$$\frac{v}{2x10} = \quad -$$

From equation (1)

$$\frac{\quad}{2x10} \qquad (\qquad)$$

$$\frac{c_p}{c_v} = \gamma$$

$$c_p = R(\frac{\gamma}{\gamma - 1})$$

$$\frac{v_2^{\,2} - v_1^{\,2}}{2x10^3} = \frac{\gamma}{\gamma - 1} P_1V_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} \right] \text{.......................... (2)}$$

4. MASS FLOW-PRESSURE RATIO RELATIONSHIP

In steady flow the rate of mass flow of fluid at any section is the same as at any other section. Consider any section f cross-sectional area A, where the fluid velocity is v, then the rate of volume flow past the section is, (vxA) the mass flow rate is

Mass flow rate

$$\dot{m} = \frac{A_2 v_2}{V_2}$$

Where $V_2 = {m^3}/{kg}$ ……………………………………(3)

and from $P_2 V^{\gamma}{}_2 = P_1 V^{\gamma}{}_1$ or $\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}}$

$$V_2 = V_1\left[{P_1}/{P_2}\right]^{\frac{1}{\gamma}}$$

$$\frac{1}{V_2} = \frac{1}{V_1}\left({P_2}/{P_1}\right)^{\frac{1}{\gamma}} = \sqrt{\frac{1}{V_1^2}\left({P_2}/{P_1}\right)^{\frac{2}{\gamma}}}$$

and from equation (3)

$$V_2 = \sqrt{2x10^3\,\frac{\gamma}{\gamma-1}P_1V_1\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$\dot{m} = A_2\sqrt{2x10^3\,\frac{\gamma}{\gamma-1}\frac{P_1}{V_1}\left[\left({P_2}/{P_1}\right)^{\frac{2}{\gamma}} - \left({P_2}/{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$

When the back pressure P_2 = the inlet pressure P_1, the air flow rate will be zero. As the back pressure is reduced, the rate f flow of air will increase until the ratio ${P_2}/{P_1}$ reaches a critical value, after which the air flow rate will remain constant.

Consider the convergent nozzle, to find the value of the of the pressure ratio of ${P_2}/{P_1}$ at which the area is a minimum it is necessary to differentiate [7].

Area (per kg/sec) = $\dfrac{\text{constant}}{\sqrt{\left({P_2}/{P}\right)^{\frac{2}{\gamma}} - \left({P_2}/{P_1}\right)^{\frac{\gamma+1}{\gamma}}}}$ differentiate with respect to $\left({P_2}/{P_1}\right)$

$$\frac{d}{d\left({P_2}/{P_1}\right)}\left[\frac{1}{\left[\left({P_2}/{P_1}\right)^{\frac{2}{\gamma}} - \left({P_2}/{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]^{\frac{1}{2}}}\right] = 0$$

5. EXPERIMENTAL WORK

The apparatus permits a comprehensive study of the laws governing the expansion of gases through nozzle as in a gas turbine as shown in Fig. (4).

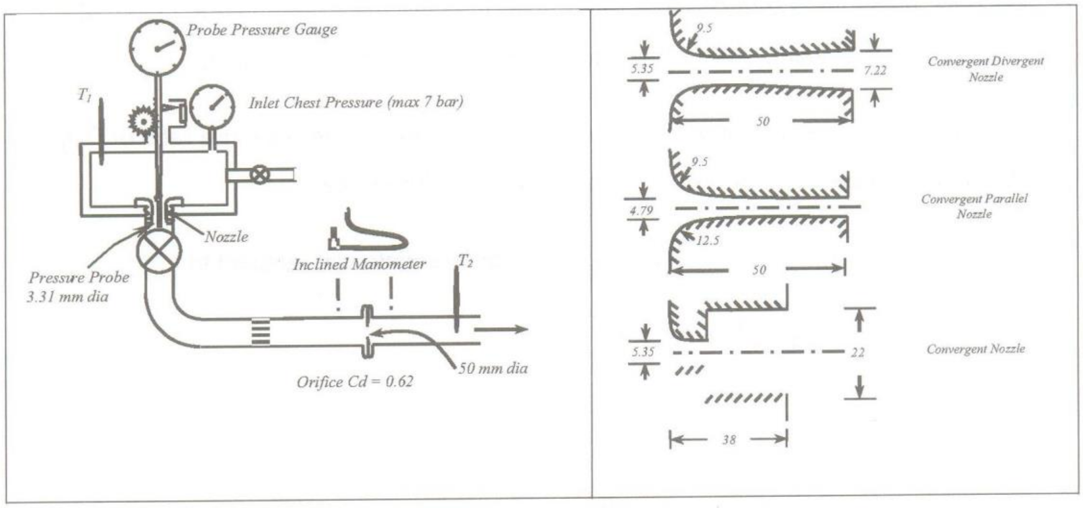
The inlet chest can be supplied with air up to 7 bars and is fitted with a throttling valve to regulate the air into the chest. A nozzle is screwed into a seating in the centre of the inlet chest, one of the three nozzles as follows

1- A convergent nozzle.
2- A convergent-divergent nozzle.
3- A convergent nozzle with parallel extension.

To enable the pressure variation along the nozzle to be observed, a stainless steel search tube or probe of diameter 3.32 mm may be traversed along the nozzle axis. Across drilling, 1.00 mm diameter into the wall of the probe transmits the local pressure to the high grade pressure gauge mounted on the probe carrier. The probe is traversed in increments of 2 mm by rotating a calibrated dial. A pointer attached to the probe carrier, moves over a replica of the nozzle profile to indicate the position of the measuring point in the nozzle. The length of probe is such that it projects well beyond the downstream end.

The nozzle discharge into a vertical tube of large bore fitted with a throttling valve by which the downstream or back pressure may be regulated. The chest also carries mercury in glass thermometer in an oil pocket, and a pressure gauge to indicate the chest pressure.

Downstream of the back pressure throttling valve, the nozzle discharge is taken by way of a long straight pipe and a flow straightened to an orifice plat with D/2 tapes to B.S.S. 1042:1943- Flow measurement. The pressure difference across the orifice-plate is indicated by an inclined manometer, permitting calculation of the air flow rate through the test nozzle. A thermometer is provided to measure temperature downstream of the orifice.



Fig, (1) Typical Apparatus and Nozzle Profile Used in Experiments

The rotary screw air compressor is first started and the supply pressure is controlled in the range 6.5 to 7 bar. The air supply valve to the inlet chest of the nozzle an apparatus is then closed and the back pressure valve is opened after making sure that the inclined manometer is correctly leveled and zeroed.

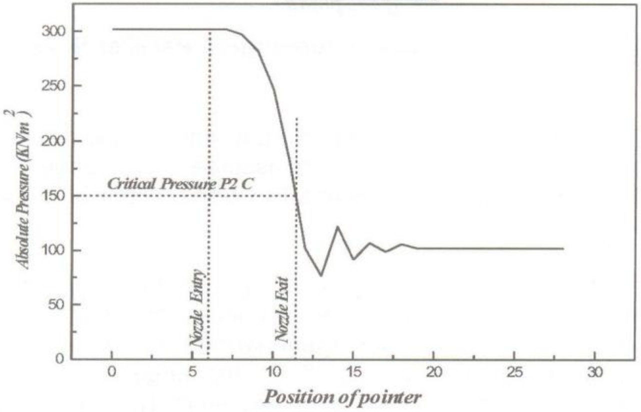
The supply valve to the inlet chest is then opened and the search tube traversed to its upper limit allowing the pressure gauge to indicate the inlet chest pressure. This could be set to the desired valve by adjusting the inlet chest valve. Attention is drawn to the tendency of the inlet chest pressure to vary during the experiment, so that it should be maintained at a constant valve.

The pressure traverse is then taken, whilst the readings of the inclined manometer, at the beginning and the end of the test, are read and an average is taken. The search tube is then returned to its upper position and the chest pressure is rechecked.

The inlet air, the down stream temperature and the barometer pressure are read in all cases.

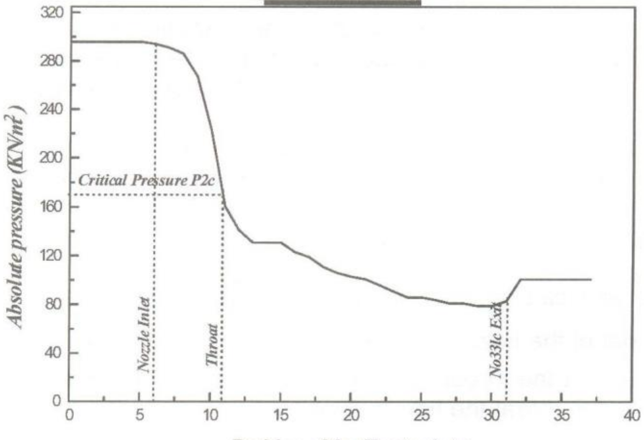
6. RESULTS AND DISCUSSION

Graph No. 1



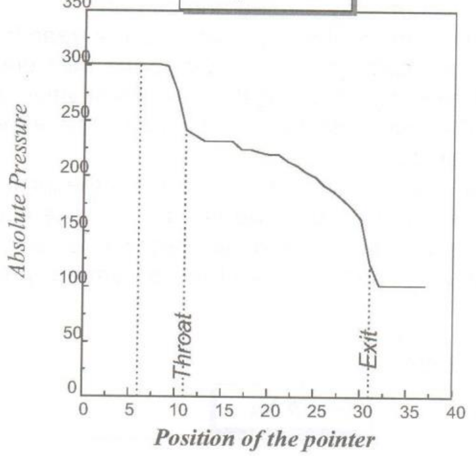
The Absolute Pressure through a convergent Nozzle

Graph No. 2



The Absolute Pressure through a convergent Nozzle

Graph No. 3



The Absolute Pressure through a convergent Parallel Nozzle

6.1 Discussion

The analysis carried out during this work is restricted to one dimensional flow where the velocity and the properties of the fluid are assumed to change only in the direction of flow and the fluid velocity is assumed to be constant at a mean value across the cross-sectional of the nozzle

The usual manner of proportioning a convergent-divergent nozzle is to determine the throat area to provide a well- rounded entrance, to choose the length of the nozzle such that the flare of the sides of the divergent section is within good limits in accordance with experience. With respect to flare, too large angle (above 15^{o}), results in excessive turbulence and consequent irreversibility, and nozzle will be excessively long if the angle is too small (less than 6^{o}). If the exit section of the nozzle is too large, over expansion occurs, that is, the gas expands to some pressure in discharge region and then rises to the discharge pressure.

If the exit section of the nozzle is too small, under expansion will occur, that is ,the pressure at the exit section will be greater than that in the discharge region, and as a result, there is a free and turbulent expansion after the substance leaves the nozzle.

Although, either over expansion or under expansion results in a loss of available energy, such operating conditions cannot be avoided at times, because of the necessity for varying output; e.g. the turbine is not always producing the same power and turbo-jet engine is not always exerting thrust.

The experiments and calculations made from the obtained data showed that, the velocity at the throat of the nozzle, operating at its designed pressure ratio (p_{2c}/p_1), is the velocity of sound at the throat conditions. The flow before and up to the throat is sub-sonic and after the throat the flow is super-sonic.

the results obtained for several tests carried out on the convergent nozzle-varying the chest inlet pressure in the range of 240 to 100 KN/m^2 and recording the corresponding values of the critical exit pressure (p_{2c}) were shown. The values, thus obtained, were compared to the theoretical values for the critical pressure obtain from the expression

$$p_{2c} = p_1\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

showed approximately the same values. The slight variations happened in some, were insignificant and were within the possible gauge error.
The procedure followed in these test could verify the validity of expression

$$p_{2c} = p_1\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

and accordingly the assumptions made the expression was derived, were valid and correct.

6.1.1 Convergent nozzle

From the data obtained graph No. (1) plotted for absolute pressure against the positions of the scale pointer along the nozzle profile, and from which, the nozzle entry, nozzle exit and the actual critical pressure could be obtained.

The gradient of the curve was so smooth, the value the pressure dropped, uniformly, indicating the expansion that was taking place inside the nozzle, up to the nozzle exit, then alight increases and continued on a fixed value (straight line).

The actual critical pressure "P_{2c}" was determined from the graph as 150 KN/m^2 and the theoretical critical pressure "P_{2c}" obtained from application of the expression P_{2c} $= P_1\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$ was = 159 KN/m^2. The two values of the critical pressure were nearly equal and the slight difference between them, is within the possible gauge error.

The actual flow rate through the nozzle calculated from the expression $m = k\sqrt{\rho_{air} dh_w}$ and m was $0.0155 m^3/Sec$ this value is compared to the theoretical mass flow rate obtained from the expression $m = \sqrt{2x10^3 . \frac{\gamma}{\gamma-1} . \frac{P_1}{V_1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]}$ was 0.02289 Kg/sec. There slight difference in the value of the mass flow rate, which falls within the possible gauge error.

6.1.2 Convergent-Parallel

The experiment carried out, using convergent nozzle, to determine the pressure ratio by varying the exit pressure and the mass flow rate of air, the pressure ratio was inversely proportional to the mass flow rate of air, that is, it decreases with the increase in the flow rate. This due to the fact that when the exit pressure is reduced, keeping the inlet pressure constant, the mass flow rate will increase consequently as the area will increase and hence with the volume flow rate and together with the inclined manometer reading h_w. Since the law governing the mass flow rate of air is given by $m = kh_w\rho_{air}$ and as k is a constant, then the factor that influence m are h_w and ρ_{air} which is $\frac{1}{v}$ (reciprocal of volume flow rate), and, therefore, any alteration in their values will result in change n the mass flow rate *(m)*

From the data, the decrease in the air exit pressure, keeping the inlet pressure constant, the volume flow rate *v*, the manometer reading, and hence the mass flow rate will continue to rise to a maximum value, and then will remain constant no matter what more reduction is carried on the inlet pressure.

6.1.3 Convergent-Divergent Nozzle

The gradient of the curve was so smooth, the value of the pressure dropped, uniformly, indicating the expansion that was taking place inside the nozzle, up to the nozzle exit, then slight increase and continued on a fix value (straight line).

The actual critical pressure value, determined from the graph was $168.0\,KN/m^2$,but the critical theoretical pressure calculated from the equation $P_{2c} = p_1\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$ equal to 155 KN/m^2,is slightly different and within the possible gauge error.

The actual flow rate of air through the nozzle calculated from the expression $\dot{m} = k\sqrt{\rho_{air}dh_w}$ where k is constant determined by experiment= 0.18825 and $\dot{m}$ was= 0.01525 Kg/sec. This value is compared to the theoretical mass flow rate m obtained from the expression $\dot{m} = \sqrt{2x10^3.\frac{\gamma}{\gamma-1}.\frac{P_1}{V_1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]}$ was= o.02289 Kg/sec.

There slight difference in the value of the mass flow rate, which falls within the possible gauge error.

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