ANALYSIS ON DETERMINATION OF LEAKAGE FLOW AND SEPARATION FORCE OF GAS TURBINE ENGINE

G. Shantha G. Sudha

Department of Mathematics & Humanities, Mahatma Gandhi Institute of Technology, Hyderabad

Corresponding Author: sudha11g@yahoo.com

ABSTRACT

Determination of leakage flow and separation force of gas turbine engine mainly seals and similar devices represents a cinque application of the qziasi-one-dimensional compressible.flow equation. This nonlinear equation has been solved numerically by varioztszithers', for nozzle, diffuser, duct, seal, and similar applications. It has been found, however, that the solitonmalteds reported in tile literature may be inoperative for seals wit11 small clearance to-length ratio, or when the seal is appreciably distorted. This deficit is cawed by a bindery layer type behaviourresulting, from a singularity in twovicinities of sonic flow, i.e., when the flow Mach number approaches unity. This new analysis considers the combined effects of entrance losses, fluid inertia, fluid,friction, area change, and,fluid turbulence and is applicable to steady, one dimensional gas,/2ow in general. The compacter program acetylates the distribution of pressure, temperature, velocity, Mach cumber, and Reynolds cycleralong the flow path.

1. INTRODUCTION

Compressible flow (or **gas dynamics**) is the branch of fluid mechanics that deals with flows having significant changes in fluid density. While all flows are compressible, flows are usually treated as being incompressible when the Mach number (the ratio of the speed of the flow to the speed of sound) is smaller than 0.3 (since the density change due to velocity is about 5% in that case).[1] The study of compressible flow is relevant to high-speed aircraft, jet engines, rocket motors, high-speed entry into a planetary atmosphere, gas pipelines, commercial applications such as abrasive blasting, and many other fields

The study of gas dynamics is often associated with the flight of modern high-speed aircraft and atmospheric reentry of space-exploration vehicles; however, its origins lie with simpler machines. At the beginning of the 19th century, investigation into the behaviour of fired bullets led to improvement in the accuracy and capabilities of guns and artillery.[2] As the century progressed, inventors such as Gustaf de Laval advanced the field, while researchers such as Ernst Mach sought to understand the physical phenomena involved through experimentation.

At the beginning of the 20th century, the focus of gas dynamics research shifted to what would eventually become the aerospace industry. Ludwig Prandtl and his students proposed important concepts ranging from the boundary layer to supersonic shock waves, supersonic wind tunnels, and supersonic nozzle design.[2] Theodore von Kármán, a student of Prandtl, continued to improve the understanding of supersonic flow. Other notable figures (Meyer, Luigi Crocco [it], and Ascher Shapiro) also contributed significantly to the principles considered fundamental to the study of modern gas dynamics. Many others also contributed to this field.

Accompanying the improved conceptual understanding of gas dynamics in the early 20th century was a public misconception that there existed a barrier to the attainable speed of aircraft, commonly referred to as the "sound barrier." In truth, the barrier to supersonic flight was merely a technological one, although it was a stubborn barrier to overcome. Amongst other factors, conventional aerofoils saw a dramatic increase in drag coefficient when the flow approached the speed of sound. Overcoming the larger drag proved difficult with contemporary designs, thus the perception of a sound barrier. However, aircraft design progressed sufficiently to produce the Bell X-1. Piloted by Chuck Yeager, the X-1 officially achieved supersonic speed in October 1947.[3]

Historically, two parallel paths of research have been followed in order to further gas dynamics knowledge. Experimental gas dynamics undertakes wind tunnel model experiments and experiments in shock tubes and ballistic ranges with the use of optical techniques to document the findings. Theoretical gas dynamics considers the equations of motion applied to a variable-density gas, and their solutions. Much of basic gas dynamics is analytical, but in the modern era Computational fluid dynamics applies computing power to solve the otherwise-intractable nonlinear partial differential equations of compressible flow for specific geometries and flow characteristics.

2. APPLICATIONS

Supersonic wind tunnels

Supersonic wind tunnels are used for testing and research in supersonic flows, approximately over the Mach number range of 1.2 to 5. The operating principle behind the wind tunnel is that a large pressure difference is maintained upstream to downstream, driving the flow.

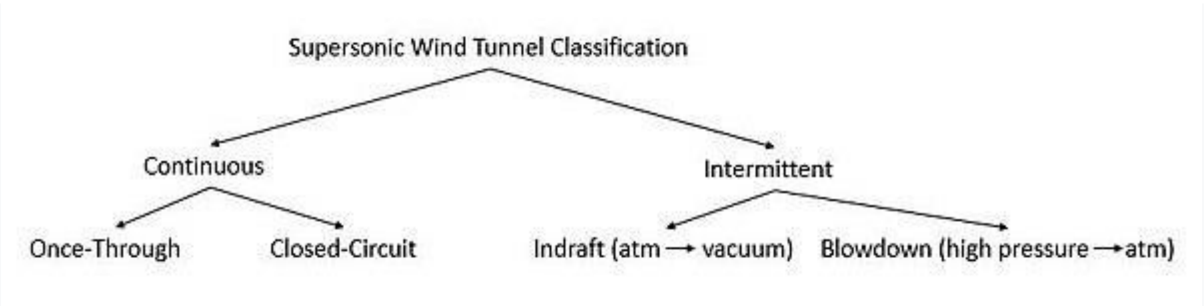


Figure 1: Supersonic wind tunnel classification list

Wind tunnels can be divided into two categories: continuous-operating and intermittent-operating wind tunnels. Continuous operating supersonic wind tunnels require an independent electrical power source that drastically increases with the size of the test section. Intermittent supersonic wind tunnels are less expensive in that they store electrical energy over an extended period of time, then discharge the energy over a series of brief tests. The difference between these two is analogous to the comparison between a battery and a capacitor.

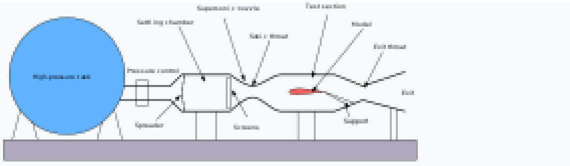


Figure 2: Blowdown supersonic wind tunnel schematic

Figure 3: Langley indraft supersonic wind tunnel vacuum sphere

Blowdown type supersonic wind tunnels offer high Reynolds number, a small storage tank, and readily available dry air. However, they cause a high pressure hazard, result in difficulty holding a constant stagnation pressure, and are noisy during operation.

Indraft supersonic wind tunnels are not associated with a pressure hazard, allow a constant stagnation pressure, and are relatively quiet. Unfortunately, they have a limited range for the Reynolds number of the flow and require a large vacuum tank.

There is no dispute that knowledge is gained through research and testing in supersonic wind tunnels; however, the facilities often require vast amounts of power to maintain the large pressure ratios needed for testing conditions. For example, Arnold Engineering Development Complex has the largest supersonic wind tunnel in the world and requires the power required to light a small city for operation. For this reason, large wind tunnels are becoming less common at universities.

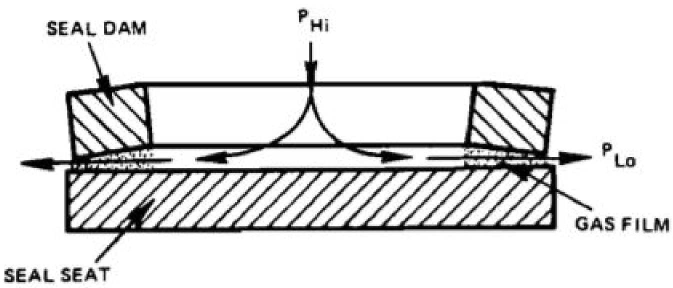
Supersonic aircraft inlets

Perhaps the most common requirement for oblique shocks is in supersonic aircraft inlets for speeds greater than about Mach 2 (the F-16 has a maximum speed of Mach 2 but doesn't need an oblique shock intake). One purpose of the inlet is to minimize losses across the shocks as the incoming supersonic air slows down to subsonic before it enters the turbojet engine. This is accomplished with one or more oblique shocks followed by a very weak normal shock, with an upstream Mach number usually less than 1.4. The airflow through the intake has to be managed correctly over a wide speed range from zero to its maximum supersonic speed. This is done by varying the position of the intake surfaces.

Although variable geometry is required to achieve acceptable performance from take-off to speeds exceeding Mach 2 there is no one method to achieve it. For example, for a maximum speed of about Mach 3, the XB-70 used rectangular inlets with adjustable ramps and the SR-71 used circular inlets with adjustable center cone.

3. THEORETICAL DEVELOPMENT

Physical Problem and Analytical Model Figure 4 shows a typical arrangement of a gas-film face seal with self-acting shrouded Rayleigh-pad features, for gas turbine engine mainshaft application. The high-pressure gas norn~ally enters the feed groove from the bore of the seal assembly and flows through the clearance space which is, in general, in the order of m (lo+ in). Since we only consider the perfectly aligned case, the primary sealing faces 'in this arrangement, i.e., the shaded area can be modeled by the separation betweeh two aligned disks as shown in Fig. 4.



Flg.4: &Analytical model of the primary sealing surfaces

The profile of the seal dam can vary as a result of thermal or other type of distortion of the seal assembly or support structures. In some applications, the seal profile may be machined to achieve certain desirable characteristics at operating conditions.

The flow path provided by the narrow spacing between the seal danl and the seat essentially resembles that of a nozzle. The flow itself is of the radial outflow or inflow type with no swirling.

Moller (I 4) as well as Zuk, Ludwig and Johnson (6) found that, in general, the radial pressure distribution of the flow, and hence the separation force, may be predicted quite accurately by numerical solution of the one-dimensional adiabatic flow equation with the consideration of the effect of fluid friction.

The analysis is restricted to subsonic or choked flow through the seal gap since, in gas turbine mainshaft applications, the combined effects of small film thickness-to-length ratio and moderate seal exit-to-entrance pressure ratio is often sufficient to prevent the formation of the kind of normal shock described by Mori (19) and Moller (13), in the gas path.

Mathematical Representation of the Problem

As discussed in the preceding section, the validity of employing the compressible quasi-one-dimensional treatment to determine the leakage flow and separation force in non-contact gas film seals is well established. Derivation of the governing equation is given here for completeness.

Assumptions adopted in this analysis are as follows:

1. The flow is one dimensional and steady

2. The fluid behaves as a perfect gas

3. The flow is adiabatic

4. Changes in flow properties are continuous

5. No external work is involved

6. The effects of surface rotation on the flow are negligible

The last assumption is adopted based on the results of an analysis presented by Zuk and Ludwig (20). The authors investigated the effects of rotation on subsonic, isothermal, compressible viscous flow in a narrow passage.

CONCLUSION

The solution technique presented in this analysis enables one to determine the leakage flow rate, separation force and center of pressure of a gas turbine face seal for design and operating conditions where the conventional method becomes inoperative. As an added benefit, the present method is not only more accurate but also more efficient in terms of computational time requirements. It is interesting to note that for the particular design and operating conditions used in this sample case, both the isentropic flow theory and the compressible viscous flow theory, based on the Reynolds equation, consistently overestimate the actual leakage flow. Furthermore, the simple isentropic flow solution yields better results than the viscous flow solution when the seal is operating at pressure ratios below 0.68 and vice versa.

REFERENCES

[1]. ANDERSON, J.D., Modern Compressible flow, McGraw Hill, 3rd Edition, 2003. Textbook available in http://a.moirier.free.fr/A%E9rodynamique/Bouquins/Anderson/Anderson%20~%20Fundamentals%20of%20Aerodynamics%20.pdf

[2]. FOX, R. W.; MCDONALD, A. T.; PRITCHARD, P. J. Introduction to Fluid Mechanics. 4. ed. Rio de Janeiro: LTC, 2006. Text book available in https://ahsheikh.github.io/Courses/NumMod/FM_RobertFox.pdf

[3]. HILL, P. AND PETERSON, C. Mechanics and Thermodynamics of Propulsion, Addison – Wesley Publishing company, 1992, available in http://soaneemrana.org/onewebmedia/MECHANICSANDTHERMODYNAMICS1.pdf

[4]. SHAPIRO, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. 1, Ronald Press, New York, 1953, book available in https://pt.scribd.com/doc/190751048/Shapiro-DynamicsThermodynamics-of-Compressible-Fluid-Flow-Volume-1

[5] F. Alobaid, Comput. Fluid Dyn. 57 (1) (2018).

[6] A. Aabid, S.A. Khan, M. Ahmed, A. Baig, A.R. Reddy, Investigation of flow growth in a duct flows for higher area ratio, IOP Conf. Ser. Mater. Sci. Eng. 1057 (012052) (2021) 10, https://doi.org/10.1088/1757-899X/1057/1/012052.

[7] A. Aabid, S.A. Khan, M. Ahmed, A. Baig, K.S. Rao, Effect of control on the duct flow at high mach numbers, IOP Conf. Ser. Mater. Sci. Eng. 1057 (012053) (2021) 9, https://doi.org/10.1088/1757-899X/1057/1/012053.

[8] M.N. Akhtar, E.A. Bakar, A. Aabid, S.A. Khan, Control of CD nozzle flow using microjets at mach 2.1, Int. J. Innov. Technol. Explor. Eng. 8 (9 Special Issue 2) (2019) 631–635, https://doi.org/10.35940/ijitee.I1128.0789S219.

[9] M.N. Akhtar, E.A. Bakar, A. Aabid, S.A. Khan, Effects of micro jets on the flow field of the duct with sudden expansion, Int. J. Innov. Technol. Explor. Eng. 8 (9 Special Issue 2) (2019) 636–640, https://doi.org/10.35940/ijitee. I1129.0789S219.

[10] S.A. Khan, A. Aabid, Z.I. Chaudhary, Influence of control mechanism on the flow field of duct at mach 1.2 for area ratio 2.56, Int. J. Innov. Technol. Explor. Eng. 8 (6 Special Issue 4) (2019) 1135–1138, https://doi.org/10.35940/ijitee. F1236.0486S419.