Research on a dielectric breakdown probe for measuring the density of a flowing gas

by Paul Matthew Jurenka

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
Montana State University

Abstract:
The use of a diagnostic probe to measure the pitot density of supersonic flow was investigated for this research. The breakdown probe operates on the well known Paschen similarity principle which states that the dielectric breakdown voltage of a gas is a function of gas density only. The effects of ionization enhancement mechanisms such as radioactivity and ultraviolet illumination on the electrodes of the breakdown gap have been investigated. The use of ultraviolet illumination greatly improves the operation of the probe. The tests using radioactivity as an ionization enhancement mechanism were inconclusive because of the relative weak strength of the radioactive source used. The Paschen theory predicts that the breakdown voltage is a function of density only and not pressure and temperature acting alone. This was proven to be the case by breakdown probe experimentation. The relations between the stream density and pitot density in supersonic flow have been resolved for different flow conditions. One relation states that the free stream density can be directly found from a measurement of the pitot density provided that the Mach number is sufficiently high. A probe tested in a supersonic flow field measured the mean pitot density reasonably well when compared with other pitot density measuring instruments. In the worst case the probe was off 30% but in the best case the probe was almost exact in measuring the pitot density. An investigation was made into using a breakdown probe for measuring turbulent density fluctuations. Only rough trends in density fluctuations were measured in supersonic flow because the instrumentation used for the fluctuation measurements proved to be unreliable.

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NOMENCLATURE

Symbol	Description
ASR	Automatic single ramp
BP	Breakdown probe
C	Celsius
CDAS	Computerized data acquisition system
d	Electrode separation distance
dc	Direct current
F	Fahrenheit
i	Current
M	Mach number
MSU	Montana State University
mil	0.001 inch
N	Total number of ramp pulses
P	Pressure
R	Gas constant
S	Sensitivity coefficient for a breakdown probe
SWT	Supersonic Wind Tunnel
T	Temperature
UV	Ultraviolet
u	Streamwise velocity component
V	Voltage
γ	Specific heat ratio

NOMENCLATURE—Continued

Γ	Electron emitted per incident position ion
τ	Voltage ramp pulse duration
ρ	Gas density
μCi	Microcurries
$\partial(\ )$	Partial derivative of quantity
d( )	Small, time-dependent fluctuation of the quantity
$(\ )'$	R.M.S. value of a property
$(\ )_b$	Condition at breakdown
$(\ )_o$	Flow stagnation property
$(\ )_p$	Probe pitot quantities
$(\ )_2$	Condition after a normal shock

ABSTRACT

The use of a diagnostic probe to measure the pitot density of supersonic flow was investigated for this research. The breakdown probe operates on the well known Paschen similarity principle which states that the dielectric breakdown voltage of a gas is a function of gas density only. The effects of ionization enhancement mechanisms such as radioactivity and ultraviolet illumination on the electrodes of the breakdown gap have been investigated. The use of ultraviolet illumination greatly improves the operation of the probe. The tests using radioactivity as an ionization enhancement mechanism were inconclusive because of the relative weak strength of the radioactive source used. The Paschen theory predicts that the breakdown voltage is a function of density only and not pressure and temperature acting alone. This was proven to be the case by breakdown probe experimentation. The relations between the stream density and pitot density in supersonic flow have been resolved for different flow conditions. One relation states that the free stream density can be directly found from a measurement of the pitot density provided that the Mach number is sufficiently high. A probe tested in a supersonic flow field measured the mean pitot density reasonably well when compared with other pitot density measuring instruments. In the worst case the probe was off 30% but in the best case the probe was almost exact in measuring the pitot density. An investigation was made into using a breakdown probe for measuring turbulent density fluctuations. Only rough trends in density fluctuations were measured in supersonic flow because the instrumentation used for the fluctuation measurements proved to be unreliable.

CHAPTER 1

INTRODUCTION

In the area of supersonic and hypersonic research there is a definite need to measure flow variables such as density, pressure, temperature, and velocity at various points in a flow. Normally, a measurement of three variables combined with the equation of state, isentropic relations, and normal shock theory will define the flow. The standard practice is to use a pitot tube to measure pitot pressure, a pitot temperature thermocouple to measure total temperature, and a static pressure sensor. A pitot density measurement combined with any two of the three measurements mentioned above would give the local flow variables. One advantage of using the pitot density measurement is that it becomes sensitive to the stream density only as the Mach number tends to infinity, as shown in Chapter 3. Thus one of the flow variables can be measured directly at high hypersonic Mach numbers with a pitot density measuring device. This research is aimed at developing a density measuring instrument called a "breakdown probe".

To the best knowledge of this author there has not been a "pitot" density measurement technique yet reported. Previous attempts at using electrical discharges to measure flow properties have included investigations by Lindvall [1] and Werner [2]. Both researchers studied the effects of using a "glow discharge" to measure pressure and velocity in subsonic flow. Other density measurement techniques include the use of optics to measure averaged density gradients.

The underlying operating principle of the breakdown probe is the well known phenomenon that the dielectric breakdown strength of a gas between two electrodes is a unique function of the gas density and the applied voltage on the electrodes. The breakdown voltage versus density characteristic of an electrode gap is characterized by the Paschen similarity principle which will be explained at the beginning of Chapter 2.

Basically, the breakdown probe and driving circuit operate as follows. First, the applied voltage difference of two closely spaced electrodes is steadily increased. The voltage difference will reach a point where a spark will jump the electrode gap as the gas is transformed from an insulator to a conductor (condition of "breakdown" explained in Chapter 2). Once breakdown has occurred, the circuit is interrupted and the breakdown voltage is recorded. The voltage necessary to initiate the spark is a unique function of the gas density for a given electrode configuration, driving circuit, and gas.

The breakdown probe is calibrated in a static environment of known gas density to determine its breakdown voltage versus density characteristic. With the characteristic known the probe can be used to measure the pitot density in a flowing gas. Since the electrodes of the probe will be located at the stagnation point on the probe tip where the fluid comes to a stop, the breakdown voltage versus pitot density characteristic is identical to the characteristic obtained in a static calibration. A measurement of the breakdown voltage in a flowing gas will therefore directly give the pitot density.

From the pitot density other flow variables such as stream density can be calculated from compressible flow theory. For instance, as stated earlier at hypersonic Mach numbers the pitot density is a known function of the stream density only. From a measurement of the pitot density the stream density can be closely estimated even at lower Mach numbers.

The goal of this research is to prove that a breakdown probe can be used to measure the density of a moving air stream. Several tests were devised to prove the utility of the probe under different operating conditions. The reliability and repeatability of the probe to measure density will be demonstrated. A more thorough discussion of the research goals will be given in Chapter 4.

CHAPTER 2

DIELECTRIC BREAKDOWN PRINCIPLE REVIEW

Introduction

The theory of dielectric breakdown of a gas is discussed in considerable detail by Cobine [3] and Flugge [4]. For brevity only the theory directly related to this research topic will be discussed.

To understand the dc breakdown of a gas, consider a gap formed in a gas by two parallel plane electrodes. An applied voltage across the electrodes will create a voltage gradient in the gas and initiate the breakdown process. The gas usually acts as an electrical insulator but can begin conducting electricity beyond a sufficient voltage potential. An observation of the voltage-current characteristic of a dc discharge along with an explanation of the electron-ion collision phenomena is needed to understand the complex events leading to the breakdown of a gas.

Primary Electrons

The breakdown events are initiated by a free electron (primary electron) that is released into the gas. The origin of these primary electrons is both natural (ambient electrons, cosmic rays, etc.) or artificial (impressed electron generation e.g. from photo-irradiation of the electrodes or the gas with ultraviolet light, X rays, radioactivity, etc.). When an electric field is applied on the electrodes the primary electrons are accelerated in the direction of the anode. The electrons eventually gain kinetic energy until they impact gas atoms with sufficient energy to produce ionization. From ionization additional free electrons and positive charged ions are