SYMPOSIUM

THE VORTEX TUBE AS A TRUE FREE AIR THERMOMETER

This volume contains reprints of papers presented at a symposium on the subject "The Vortex Tube as a True Free Air Thermometer", held at the Armour Research Foundation, Chicago, Illinois on May 24, 1955.

The symposium was organized at the request of the Air Research and Development Command, Wright Air Development Center, Dayton, Ohio, for the purpose of exchanging information among the various organizations engaged in research programs on this subject.

Papers were presented by seven organizations with subjects ranging from the theoretical aspects of flow in vortex tubes to a description of the actual use of vortex thermometers for free air temperature measurement from aircraft.

The sponsors of the symposium wish to thank the authors and other participants who helped to make the meeting a success. Special acknowledgement is due Mr. K. W. Miller of the Armour Research Foundation and Mr. R. L. Fine of the Wright Air Development Center, who served as chairmen of the sessions...

H. A. Leedy

H. A. Leedy
Director

HELD MAY 24, 1955 AT

ARMOUR RESEARCH FOUNDATION

THERMAL PHENOMENA IN A VORTEX

by

C. Desmond Pengelley
Southwest Research Institute
San Antonio, Texas
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INTRODUCTION

In 1952 Southwest Research Institute carried out a program to determine the commercial feasibility of using the Hilsch tube principle in place of a conventional expansion turbine to obtain a significant temperature drop while expanding a gas from high to low pressure. It was intended that energy should be taken from the system by transferring heat from the hot outlet through a radiator to atmosphere and then mixing the resultant gas with the cold stream to obtain a total flow with reduced temperature. The heat removed at the radiator would be the equivalent of work done by an expansion turbine.

For various reasons, this program was not carried to conclusion, the principle one being that no method was found to describe the basic mechanism by which the device worked. Design predictions for commercial sized units therefore could not be made based on results obtained with laboratory bench models and speculative funds were not available for full scale testing.

It is the purpose of this paper to present certain experimental data that were obtained in the laboratory during this program and to outline a hypothesis of the writer pertaining to the fundamental mechanism involved.

EXPERIMENTAL RESULTS

Two bench size Hilsch tubes were made. One was approximately ½ in. diameter and the other 5 in. diameter. Due to limitations and the laboratory air supply, high velocities could not be achieved in the large tube and relatively small temperature differentials were obtained. Nevertheless, the size was such that it was possible to measure local stream lines and velocities.

With the small tube high velocities and large temperature differences were possible but flow measurements could not be made. The greatest temperature difference obtained was with the small tube using a .18 in. bleed hole on the cold side and 80 psi gauge pressure at the inlet nozzle. The following results were obtained:

Stagnation temperature of incoming air	72°F
Hot outlet	101°F
Cold orifice	-37°F

The large tube was 5 in. in diameter and 12 in. long. The bleed hole size of the cold end was 3/16 in. in diameter and the outlet at the hot end was ½ in. diameter with an adjustable valve. Stagnation pressure of the inlet flow was 14 psi gauge and a temperature of 83°F.

Under these conditions a probe of 1/16 in. diameter hypodermic tubing was made to measure total head and static pressure and direction of resultant flow. This probe used an orifice .013 in. diameter. Traverses were made at the inlet plane and at stations towards the hot side at the following distances down the tube: 1½ in., 3 in., 6 in., and 12 in. The helix angle of the flow was at all times less than the sensitivity of the instrumentation (less than 3 degrees).

The experimental data have been summarized on Figure 1. It will be seen that at the inlet plane tangential velocity is high at the circumference and decreases to a minimum at approximately $\frac{1}{2}$ the radius of the tube; from this point inward, it increases and approximates the distribution of a free vortex, except for the central core in which the resolving power of the probe was insufficient to detect variations. At stations further removed from the inlet plane, it can be seen that the circumferential velocity decreases, as might be expected, and the overall flow approximates that of a free vortex, except for indeterminacy very close to the center.

For the flow shown on Figure 1, the following conditions existed:

Hot side temperature	83°F
Cold side temperature	58°F
Inlet temperature	? 89°F 79°F
Room temperature	77°F
Inlet pressure	**14 psi gauge**
Flow through hot outlet	24.2 cfm
Flow through cold outlet	12.5 cfm

Stagnation pressures were found to decrease at the center as shown in Figure 1. This is consistent with the low temperature measured at the outlet; however, it was not possible with the apparatus at hand to measure actual local temperatures in the flow.

Empirical expressions were set up to represent the flow pattern and estimates indicated that commercial feasibility might be possible, though not conclusively predictable.

MECHANISM OF THE HILSCH TUBE

In spite of the vast bibliography that exists on the Hilsch tube and related phenomena, the writer does not know of any physical explanation of the mechanism by which it operates. A hypothesis is presented, therefore, which is believed to present a reasonably probable picture of the actual behavior.

First, consider the velocity distribution in two different kinds of circular flow. These are as follows:

1. A centrifuge with no radial flow and with viscosity.
2. A conventional vortex without viscosity and with radial flow.

For Type (1) a finite quantity of gas can be imagined completely enclosed in a whirling cylinder. Due to viscosity the steady state condition of the system will result in a velocity distribution having no viscous shear forces. This condition is met when the tangential velocity is directly proportional to the radius, that is to say, when the angular velocity is constant and the gas rotates as a rigid body.

Type (2) flow consists of a conventional vortex or whirlpool. This results when a pressure sink exists in the presence of a large supply of fluid. Neglecting the effect of viscosity, acceleration towards the sink will occur in response to a small pressure gradient. The velocity distribution will be according to Bernoulli's equation, velocity head being gained at the expense of static pressure. This results in circular flow about the sink, the tangential velocity being inversely proportional to the radius.

Acceleration will continue as long as the pressure gradient exists and when it is removed the vortex will continue with constant strength. In actual practice, a pressure gradient and a finite flow must be maintained of a sufficient magnitude to put energy into the system equivalent to the heat energy that is being generated by viscous effects.

It is evident that temperature in the vortex will decrease toward the center as the velocity increases according to the conventional laws of the expansion of ideal gas. However, neglecting viscosity, there is no conceivable way in which this high velocity, low temperature gas can be slowed down without returning to stagnation conditions -- it cannot therefore be used as a low temperature sink. Due to viscosity, the tangential velocities, of course, cannot reach infinity and, as mentioned previously, there must be a central core rotating essentially as a rigid body. There will also be a transition section over a definite radius in which the flow cannot be approximated by either of the limiting types.

The velocity distribution in the core will be of Type (1) as described previously, having constant angular velocity and no viscous forces. Since, by definition, no radial flow exists in a centrifuge, Bernoulli's theorem will have no effect upon velocity distribution under steady state conditions. The radial pressure gradient at any radius will be directly proportional to the density and angular acceleration. This means that gas at the circumference of the centrifuge will have maximum pressure and it will decrease as the center is approached. Effectively, the gas will find itself in a gravity field set up by the action of the centrifuge. This is equivalent to the situation that exists in the atmosphere. It is well known that the steady state condition results in a stable lapse rate, with the temperature decreasing as the pressure decreases. The relationship between pressure and temperature is a function of heat conductivity in the gas. If it were zero, an adiabatic lapse rate would exist as one extreme, and if it were infinite, an isothermal lapse rate would exist as the other. Without solving the exact gas equations for equilibrium within a centrifuge, it can be seen by inspection that under steady state conditions with no radial flow, a lapse rate must exist with temperature decreasing towards the center.

In a Hilsch tube, therefore, we can imagine conventional vortex flow from the circumference in to some critical radius, centrifuge flow from the center out to a somewhat smaller critical radius, and transitional flow between these two critical radii. Because of viscous effects, a total pressure drop and a finite radial flow is essential through the vortex region in order to maintain the vortex at a constant strength. This radial flow must have an outlet in order to maintain steady state conditions.

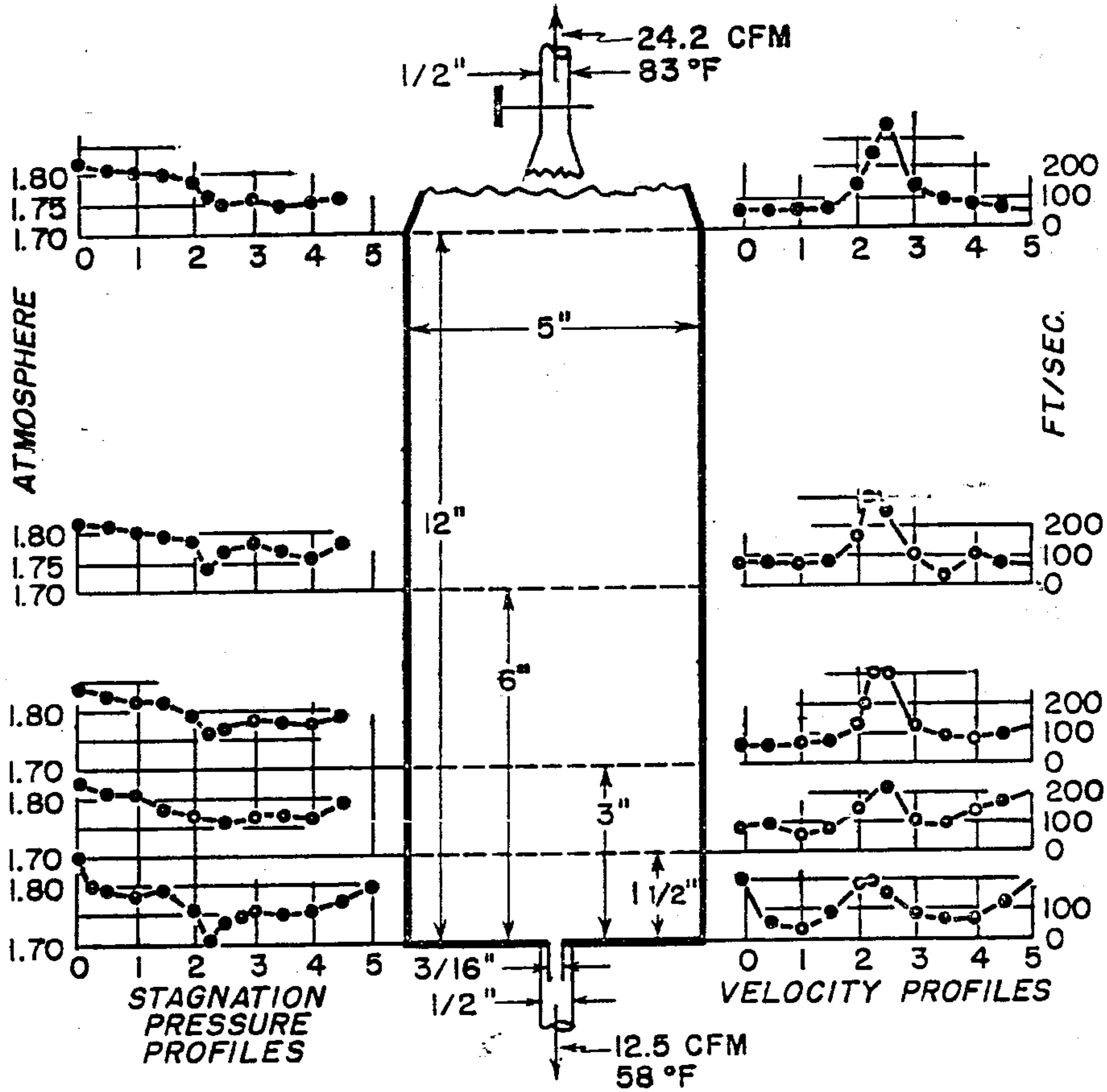
In a typical Hilsch tube in which the cold orifice is plugged the entire flow goes out the hot orifice. Its temperature rise will be due to viscous heat generated in the vortex. As the flow approaches the hot outlet, turbulence will tend to break down the vortex pattern, as well as the steady state condition of the core and too, will tend to mix and pass out of the hot orifice as a turbulent stream. At an appreciable distance up stream from the hot orifice, however, axial flow will be slight and there is nothing to prevent the formation of a solid core acting as a steady state centrifuge with zero radial flow, and exhibiting a temperature lapse rate towards the center.

Visualize now a plane perpendicular to the axis of the tube and taken close to the station of the cold orifice and well removed from the hot orifice. As one moves radially inwards from the circumference, increasing velocities will be experienced with decreasing pressures and temperatures. Some axial component of flow will exist, until finally one approaches the transition region. In the transition region, viscous forces will tend to decelerate the gas working against the pressure gradient in much the same way as in a boundary layer. Temperatures will rise but since the main effect of the viscous forces is to change the acceleration and not the velocity, the temperature rise in the transition region will be small. As the transition region is passed, one approaches the circumference of the solid core where the heating effect and radial component of flow will both approach zero, and where temperature and velocity both decrease towards the center.

The foregoing explains the presence of a low temperature core in a flowing vortex. Flow through the cold orifice of a Hilsch tube can be visualized as follows: Imagine that steady state conditions have been established and a cold core exists. A bleed tube may be installed and the cold core removed. This operation will immediately produce radial flow in the centrifuge. Such radial flow will result in Coriolis acceleration and momentarily increase angular velocity at the center and consequently the generation of viscous heat. This increase in heat generation will be the equivalent of the brake horsepower that must be removed from an expansion turbine in order to obtain cooling of a compressed gas. When the cold air in the core has been removed, the bleed hole may be closed. After a short time, steady state conditions will again be set up and another sample of air from the cold core may be withdrawn. It can be seen that each time a cold sample is drawn, additional heat is generated and passed out of the hot orifice. This process can be carried out uniformly by reducing the rate of flow through the bleed and increasing the frequency of sampling until it becomes continuous.

It is evident, therefore, that the Hilsch tube mechanism is similar to that of an expansion turbine in which viscous forces within the gas are used to remove energy from the gas whenever cold air is withdrawn. Continuous flow through the hot orifice must be maintained in order to provide the energy necessary to keep the vortex at steady state conditions. This is essentially "a fluid drive transmission", which is needed to keep the centrifuge going. In order to increase efficiency of a Hilsch tube, therefore, it is necessary to improve the efficiency of the "fluid drive". Just how to do this is the $64 question. In general, the requirement is to keep vortex flow to a minimum and maintain as much centrifuge type flow as possible. Once this has been achieved there is no reason to suppose that the "turbine power" which must be removed at the hot side when actual cold flow exists, will be appreciably different from the actual brake horsepower taken from an expansion turbine and dissipated in the form of heat through a dynamometer.

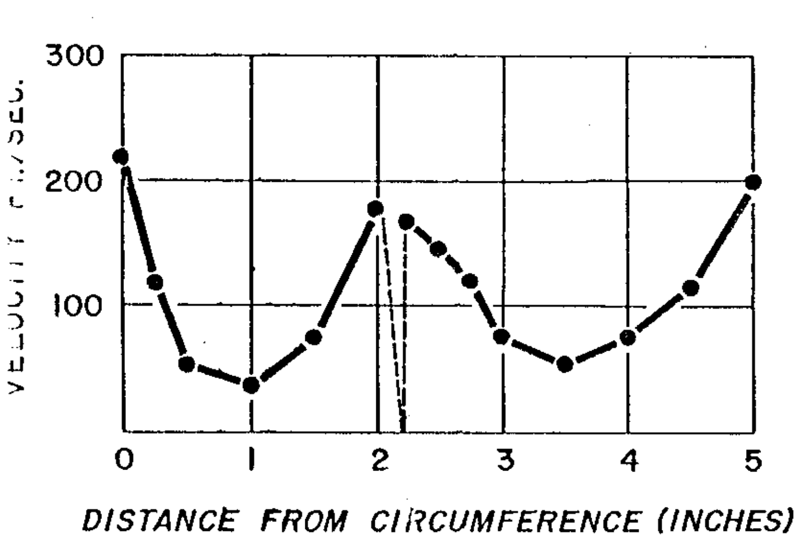
There is no reason that by suitable design of the flow chamber, thermodynamic efficiencies of the Hilsch tube could not be made to approach those of an expansion turbine without the introduction of moving parts.



FLOW PATTERN

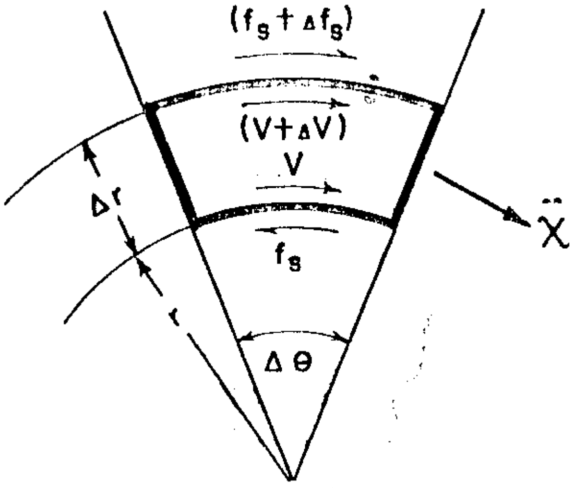
INLET PRESSURE 14 PSI GAGE
INLET TEMPERATURE 81 °F

FIG. 1



VELOCITY DISTRIBUTION
at
INLET PLANE

FIG. 2



ACCELERATION

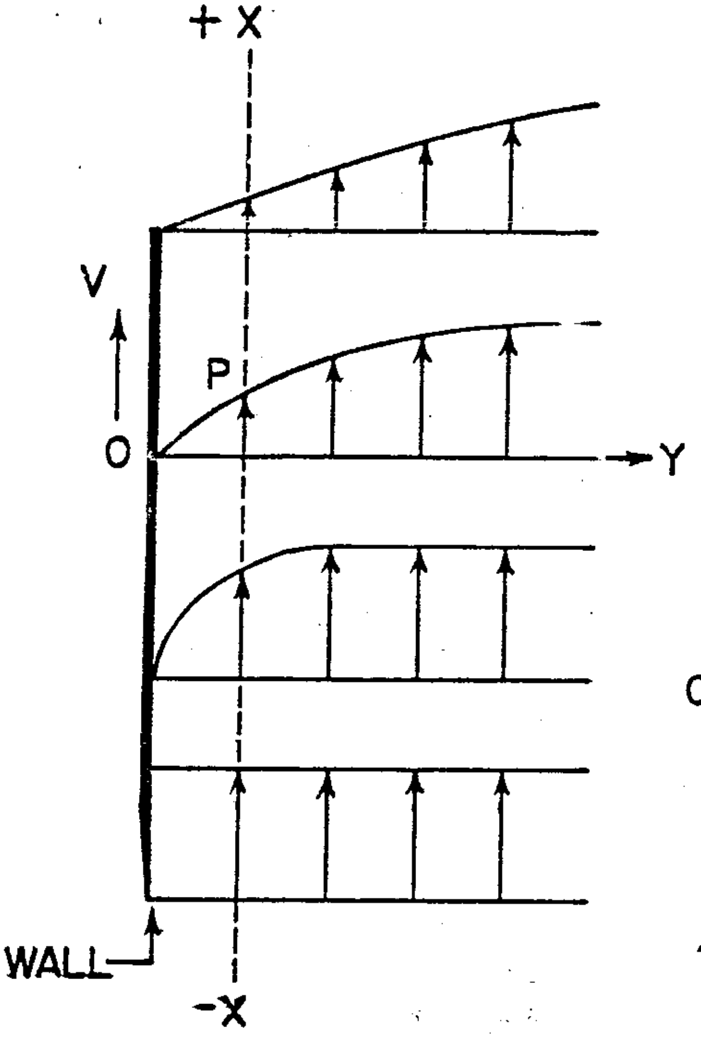
$$\ddot{X} = \frac{\mu}{\rho}\left[\frac{d^2 v}{dr^2} + \frac{1}{r}\left(\frac{dv}{dr} - \frac{v}{r}\right)\right]$$

HEAT GENERATED PER UNIT MASS

$$H = \frac{\mu}{\rho J}\left(\frac{dv}{dr} - \frac{v}{r}\right)^2$$

VISCOUS & INERTIA FORCES IN VORTE

FIG. 3



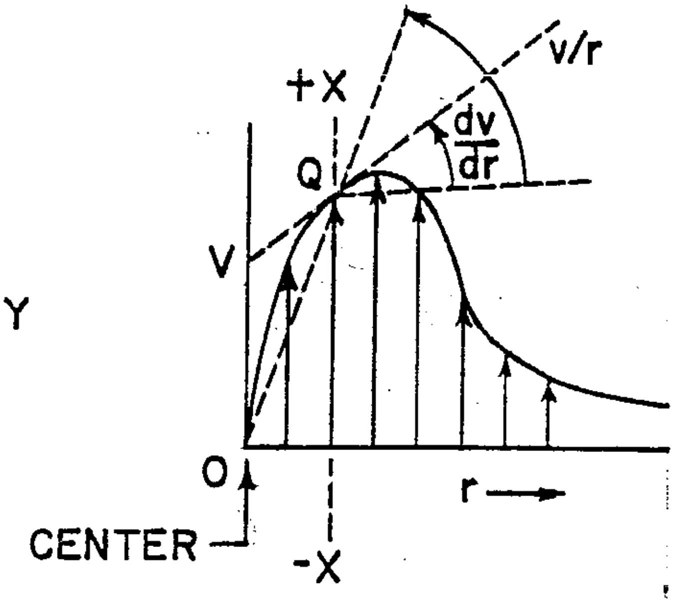
FLOW IN BOUNDARY LAYER

ACCELERATION

$$\ddot{X} = \frac{\mu}{\rho}\frac{d^2v}{dy^2} \sim \text{NEG. NUMBER}$$

HEAT GENERATED PER UNIT MASS

$$H = \frac{\mu}{\rho J}\left(\frac{dv}{dy}\right)^2$$



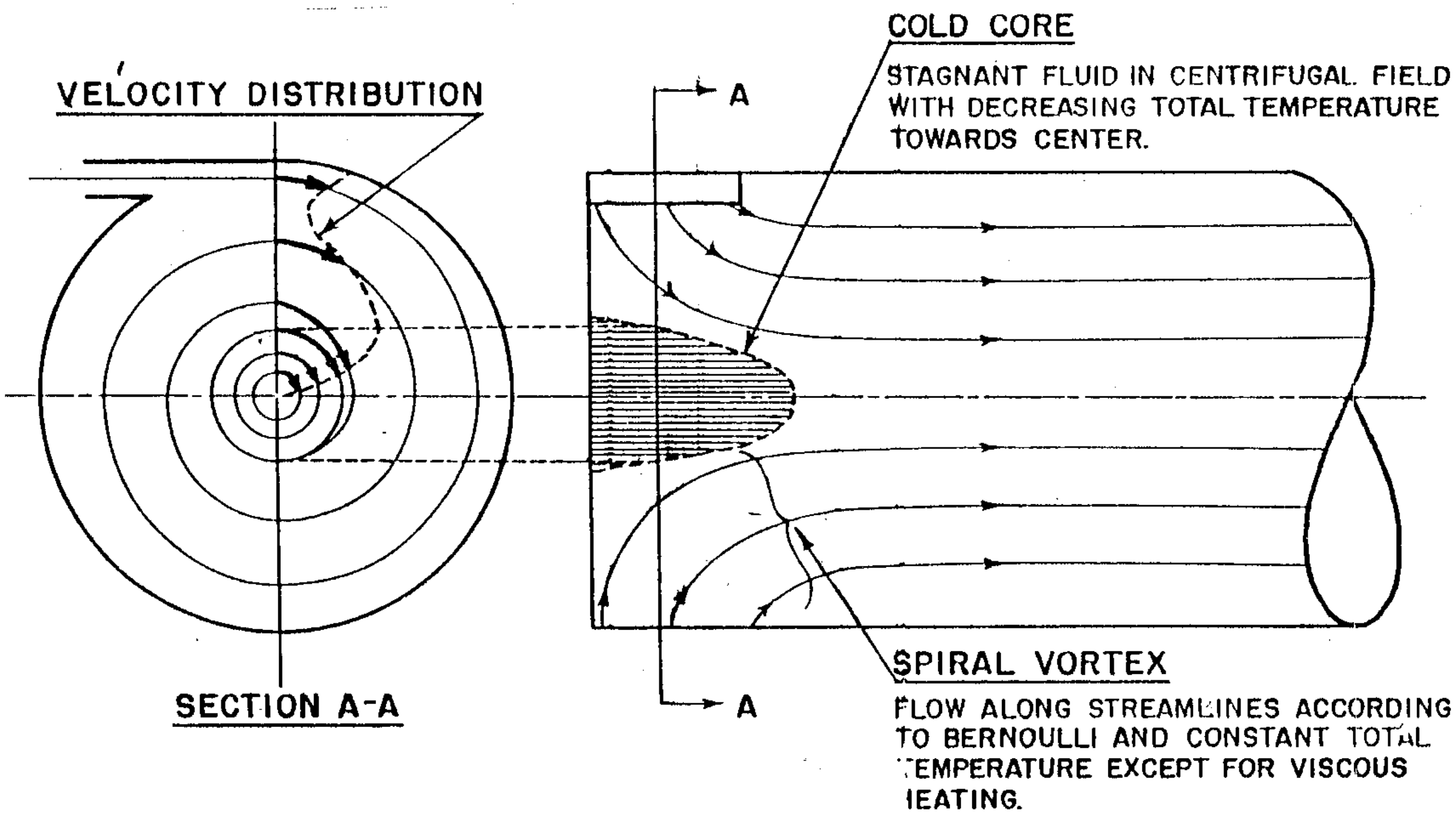
FLOW IN VORTEX CORE

$$\ddot{X} = \frac{\mu}{\rho}\left[\frac{d^2v}{dr^2} + \frac{1}{r}\left(\frac{dv}{dr} - \frac{v}{r}\right)\right]$$

$$H = \frac{\mu}{\rho J}\left(\frac{dv}{dr} - \frac{v}{r}\right)^2$$

COMPARISON BETWEEN BOUNDARY LAYER AND VORTEX CORE

FIG. 4



FLOW IN VORTEX TUBE

SPIRAL VORTEX BUILDS UP HIGH VELOCITY AND DRIVES CENTRAL CORE BY VISCOUS FORCES WHICH APPROACH ZERO IN CORE WHEN NO FLOW EXISTS.

FIG. 5