



Natural convective flow patterns between an isothermal heated inner body and an isothermal cooled cubical enclosure
by Lucius Loren Eyler

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Mechanical Engineering
Montana State University
© Copyright by Lucius Loren Eyler (1973)

Abstract:

Qualitative analyses of the natural convective flow between isothermal heated inner bodies and an isothermal cooled cubical enclosure are presented. Five inner bodies were investigated with diameters ranging from 3.5 inches to 9.0 inches. The cubical enclosure was 9.9 inches on a side. The inner bodies were located concentrically in the cubical enclosure. Air was the gap working fluid and cigar smoke provided the tracer particles used to visualize the flow.

The flow in the gap for the 3.5 inch and 4.5 inch inner bodies was steady for all the temperature differences investigated. The resulting flow was characterized by three distinct regions; a high speed boundary region, an upper interior region characterized by at least one eddy formation, and a slower moving lower region. The 5.5 inch inner body exhibited similar flow for the lower temperature differences.

For the higher temperature differences, a periodic unsteady flow was noted in the upper central region in the form of a pulsating spiral eddy formation. The largest inner bodies, 7.0 inch and 9.0 inch spheres, exhibited nonperiodic unsteady flow for all the temperature differences investigated. This unsteady flow was characterized by the upward high speed flow separating from the inner body and a random "falling" of a slug of fluid from the upper vertical axial region into the upper central region. The slug of fluid would momentarily disrupt the flow in the upper central region. In general, the flow was noted to be symmetric, with respect to the cube's diagonal vertical planes and the cube's perpendicular vertical planes, for the steady flow cases and nonsymmetric for the unsteady flow cases.

In presenting this thesis to the Graduate Faculty in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering at Montana State University, I agree that the library shall make it freely available for inspection. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by my major professor, or, in his absence, by the Director of the Libraries. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature L. L. Brown
Date 7/31/73

NATURAL CONVECTIVE FLOW PATTERNS BETWEEN AN ISOTHERMAL
HEATED INNER BODY AND AN ISOTHERMAL
COOLED CUBICAL ENCLOSURE

by

LUCIUS LOREN EYLER, JR.

A thesis submitted to the Graduate Faculty in partial
fulfillment of the requirements for the degree

of

MASTER OF SCIENCE

in

Mechanical Engineering

Approved:

M. Bishop
Head, Major Department

J. B. ...
Chairman, Examining Committee

Henry I. Parsons
Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

August, 1973

ACKNOWLEDGEMENT

The author wishes to express his many thanks to all who have contributed their time and effort in the completion of this work. Special thanks are due to Dr. J. A. Scanlan, Dr. R. E. Powe, and Dr. E. H. Bishop for their assistance in being associated with this work. Thanks goes to Dr. W. A. Hunt for his role on the author's Graduate Committee. The technical assistance provided by the Mechanical Engineering machine shop was also greatly appreciated. Finally, a special thought is given to his wife, Vicki Lee, for her kind patience and understanding during the completion of this work.

The work completed by this report was supported by the National Science Foundation under Grant Number GK-31908, the Atomic Energy Commission under AEC Contract AT(45-1)-2214, and by the Mechanical Engineering Department at Montana State University.

TABLE OF CONTENTS

Chapter	Page
VITA	ii
ACKNOWLEDGEMENT	iii
LIST OF FIGURES	v
ABSTRACT	vii
NOMENCLATURE	viii
I. INTRODUCTION	1
II. LITERATURE REVIEW	4
III. EXPERIMENTAL APPARATUS AND PROCEDURE	10
EXPERIMENTAL APPARATUS	10
EXPERIMENTAL PROCEDURE	22
IV. EXPERIMENTAL RESULTS	24
FLOW PATTERN DESCRIPTIONS	27
SUMMARY OF RESULTS	61
V. CONCLUSION	67
APPENDIX. COMPUTER PROGRAM	70
BIBLIOGRAPHY	75

LIST OF FIGURES

Figure	Page
3.1 Experimental Apparatus	11
3.2 Schematic Showing the Support Equipment	12
3.3 Cutaway Drawing of the Sphere-Cube-Jacket Arrangement	13
3.4 Drawing Showing the Orientation of the Planes in which the Flow was Observed	15
3.5 Interior of Inner Sphere	19
4.1 Flow Pattern in the Perpendicular Vertical Plane for ID = 3.5 inches, $\Delta T = 24^{\circ}\text{F}$, $N_{\text{Gr}} = 626,000$	28
4.2 Flow Pattern in the Diagonal Vertical Plane for ID = 3.5 inches, $\Delta T = 33^{\circ}\text{F}$, $N_{\text{Gr}} = 758,000$	31
4.3 Flow Pattern in the Perpendicular Vertical Plane for ID = 3.5 inches, $\Delta T = 113^{\circ}\text{F}$, $N_{\text{Gr}} = 1,862,000$	32
4.4 Flow Pattern in the Horizontal Midplane for ID = 3.5 inches, $\Delta T = 108^{\circ}\text{F}$, $N_{\text{Gr}} = 1,828,000$	35
4.5 Flow Pattern in the Perpendicular Vertical Plane for ID = 4.5 inches, $\Delta T = 30^{\circ}\text{F}$, $N_{\text{Gr}} = 447,000$	37
4.6 Flow Pattern in the Diagonal Vertical Plane for ID = 4.5 inches, $\Delta T = 89^{\circ}\text{F}$, $N_{\text{Gr}} = 920,000$	39
4.7 Flow Pattern in the Perpendicular Vertical Plane for ID = 5.5 inches, $\Delta T = 28^{\circ}\text{F}$, $N_{\text{Gr}} = 206,000$	41
4.8 Flow Pattern in the Upper Central Region of the Perpendicular Vertical Plane for ID = 5.5 inches, $\Delta T = 28^{\circ}\text{F}$, $N_{\text{Gr}} = 206,000$	44
4.9 Flow Pattern in the Diagonal Vertical Plane for ID = 5.5 inches, $\Delta T = 29^{\circ}\text{F}$, $N_{\text{Gr}} = 229,000$	46
4.10 Flow Pattern in the Horizontal Midplane for ID = 5.5 inches, $\Delta T = 29^{\circ}\text{F}$, $N_{\text{Gr}} = 227,000$	48

Figure		Page
4.11	Flow Pattern in the Perpendicular Vertical Plane for ID = 7.0 inches, $\Delta T = 9^{\circ}\text{F}$ (error 41%), $N_{Gr} = 21,800$	50
4.12	Flow Separation from the Inner Body in the Per- pendicular Vertical Plane for ID = 7.0 inches, $\Delta T = 9^{\circ}\text{F}$ (error 41%), $N_{Gr} = 21,800$	51
4.13	Flow Pattern in the Diagonal Vertical Plane for ID = 7.0 inches, $\Delta T = 10^{\circ}\text{F}$ (error 30%), $N_{Gr} = 27,200$	52
4.14	Flow Pattern in the Perpendicular Vertical Plane for ID = 9.0 inches, $\Delta T = 14^{\circ}\text{F}$, $N_{Gr} = 1,070$	57
4.15	Flow Pattern in the Perpendicular Vertical Plane for ID = 9.0 inches, $\Delta T = 14^{\circ}\text{F}$, $N_{Gr} = 1,070$	58
4.16	Flow Pattern in a Horizontal Plane Section at the Midplane for ID = 9.0 inches, $\Delta T = 14^{\circ}\text{F}$, $N_{Gr} = 950$	62

ABSTRACT

Qualitative analyses of the natural convective flow between isothermal heated inner bodies and an isothermal cooled cubical enclosure are presented. Five inner bodies were investigated with diameters ranging from 3.5 inches to 9.0 inches. The cubical enclosure was 9.9 inches on a side. The inner bodies were located concentrically in the cubical enclosure. Air was the gap working fluid and cigar smoke provided the tracer particles used to visualize the flow.

The flow in the gap for the 3.5 inch and 4.5 inch inner bodies was steady for all the temperature differences investigated. The resulting flow was characterized by three distinct regions; a high speed boundary region, an upper interior region characterized by at least one eddy formation, and a slower moving lower region. The 5.5 inch inner body exhibited similar flow for the lower temperature differences. For the higher temperature differences, a periodic unsteady flow was noted in the upper central region in the form of a pulsating spiral eddy formation. The largest inner bodies, 7.0 inch and 9.0 inch spheres, exhibited nonperiodic unsteady flow for all the temperature differences investigated. This unsteady flow was characterized by the upward high speed flow separating from the inner body and a random "falling" of a slug of fluid from the upper vertical axial region into the upper central region. The slug of fluid would momentarily disrupt the flow in the upper central region. In general, the flow was noted to be symmetric, with respect to the cube's diagonal vertical planes and the cube's perpendicular vertical planes, for the steady flow cases and nonsymmetric for the unsteady flow cases.

NOMENCLATURE

Symbol	Description
a, b	Characteristic lengths
C_p	Specific heat
d, e, f	Empirical constants
Dev	Deviation (defined by eq. 4.2)
g	Acceleration of gravity
h	Coefficient of convection
k	Thermal conductivity
L	Length parameter (defined by eq. 2.3)
N_{Gr}	Grashof number (defined by eq. 2.1)
N_{Nu}	Nusselt number (defined by eq. 2.5)
N_{Pr}	Prandtl number (defined by eq. 2.2)
N_{Ra}	Rayleigh number (defined by eq. 2.6)
T_{am}	Arithmetic mean temperature (defined by eq. 4.1)
$T_{i,ave}$	Average inner body temperature
T_l	Local outer body temperatures
$T_{o,ave}$	Average outer body temperature
ΔT	Difference between the average inner body temperature and the average outer body temperature
β	Coefficient of thermal expansion

Symbol	Description
μ	Dynamic viscosity
ρ	Density

CHAPTER I

INTRODUCTION

The purpose of this paper is to qualitatively relate the experimental results obtained during investigations of the flow characterizations of air in a finite enclosure. The finite enclosure consisted of an inner spherical body, supported on a stem and concentrically located in a cubical enclosure. Flow in the enclosure was created by heating the inner sphere and cooling the outer enclosure, resulting in a natural convection process.

In recent years, experimental work in this area has contributed significantly to the overall understanding of natural convection phenomena in the area of natural convection heat transfer between a given body and an enclosure. Work has shown that empirical relations can be obtained to correlate experimental data relating the heat transferred by natural convection between certain body shapes and a spherical enclosure (1,2,3)*. Concurrent work has also shown that flow visualization methods aid in describing the heat transfer results (4,5).

The apparent need for experimental work in this area stems from the realization that analytical work in this area is difficult. The set of differential equations governing

* Underlined numbers in parentheses refer to references cited in the bibliography.

natural convection heat transfer in enclosed regions has not been solved because the usual simplifying assumptions involving the boundary layers, boundary conditions, and pressure gradients cannot be made. Thus, the coupled, non-linear, partial differential equations are amenable to no general solution. Consequently, due to lack of any general solution of the problem of natural convection heat transfer in finite enclosures, experimental work necessarily requires both empirical relations for heat transfer data and visualization of the fluid flow in order to adequately describe the interaction of the thermal and hydrodynamic effects.

Several possible extensions of the work done in this area can be thought of. As examples, considerations can be made of its application to electronic instrument packaging, spent fuel container design, in-pile experiments, and fire fighting techniques. However, it must be kept in mind that these are possible projected applications and in the present work no direct application is attempted.

The work completed and results obtained during the preparation of this thesis contribute to the presently available information in the area of natural convection heat transfer in a finite enclosure. Also, it is part of a continuing project at Montana State University. Closely related

work in this area was conducted by Baughman (5) and Yin (4) and reference is made to any similar results and conclusions they reached. However, they utilized a spherical enclosure rather than a cubical enclosure. This work is apparently the first of its kind which utilizes a cubical enclosure, thus adding a new contribution to this particular area of heat transfer.

CHAPTER II
LITERATURE REVIEW

Free or natural convection heat transfer is a form of energy transfer resulting from motion of a fluid due to density differences. The density of a fluid, whether a liquid or gas, generally changes in the proximity of a heat source, thus causing a bouyancy force which results in the fluid motion. However, without the presence of an external force, such as gravity or rotation, the bouyancy force would not arise.

As previously noted, analytical solution of natural convection systems is generally quite complex. Solutions are available for several simple configurations for free convection to an infinite medium and for several enclosed regions (6,7,8). Consequently, a number of experimental investigations have been reported for more complex geometries including several enclosed regions.

The dimensionless parameters involved in a free convection system have been determined by both the differential and dimensional methods. Both methods are reported by Jakob (7), and the important resulting dimensionless groups are

$$N_{Gr} = \frac{\rho^2 g \beta (T_i - T_o) a^3}{\mu^2}, \quad (2.1)$$

$$N_{Pr} = \frac{C_p \mu}{k}, \quad (2.2)$$

$$\text{and } L = \frac{a}{b} . \quad (2.3)$$

N_{Gr} is the Grashof number and N_{Pr} is the Prandtl number. The length parameter, L , is a ratio of the two characteristic dimensions, a and b , of the system under investigation.

Also reported by Jakob is a relation for correlating heat transfer. It has been proposed that

$$N_{Nu} = d \cdot (N_{Gr})^e \cdot (N_{Pr})^f \quad (2.4)$$

where d , e , and f are constants that must be determined experimentally. N_{Nu} is the Nusselt number given by

$$N_{Nu} = \frac{ha}{k} \quad (2.5)$$

where a is a characteristic dimension of the system under investigation. Another oftentimes very convenient dimensionless group is the Rayleigh number, given by the product of the Grashof number and the Prandtl number, or

$$N_{Ra} = N_{Gr} \cdot N_{Pr} . \quad (2.6)$$

A series of experimental works has been reported considering the natural convection flow process in a spherical annulus. Flow visualization of the basic case of concentric isothermal spheres was first investigated by Bishop (1).

He used air as the gap working fluid and investigated diameter ratios of 1.19, 1.37, 1.72, 2.53, and 3.14. He investigated temperature differences of 5°F up to a maximum of 60°F. An extension of the concentric isothermal spheres using air as the gap working fluid was conducted by Yin (4). He investigated diameter ratios of 1.40, 1.78, and 2.17. His results extended the Grashof number to 1,156,000.

Both researchers reported the flow visualization in terms of the flow patterns observed. The former work initially noted three common patterns. These were named (1) the "crescent-eddy" type, (2) the "kidney-shaped-eddy" type, and (3) the "falling-vortices" type.

Bishop observed the "crescent-eddy" pattern for diameter ratios of 1.37 and 1.72 for all the temperature differences investigated, while with diameter ratios of 1.19, 2.53, and 3.14, the "crescent-eddy" pattern occurred only for lower temperature differences. The "kidney-shaped-eddy" pattern occurred for diameter ratios of 2.53 and 3.24 for moderate to high differences in temperature. The last pattern, the "falling-vortices" type, was the only unsteady pattern noted by Bishop, and occurred only for a diameter ratio of 1.19 at moderate to high temperature differences. All of the steady patterns investigated were reported to be characterized by three flow regions. These regions were

(1) a thin high speed layer immediately adjacent to each solid boundary, (2) a low speed central region, and (3) a transition region between the former two regions. In addition, a relatively stagnant region was noted in the lower portion of the annulus for some cases. The one unsteady flow was characterized by the apparent periodic formation of counter-rotating vortex pairs near the upper vertical axis. The vortices would form, then coalesce and "fall" into the central-eddy region, momentarily disrupting the central region.

Yin's results consisted of repeating and verifying some of the results obtained by Bishop, and investigating higher temperature differences and other fluids. Comparison of the results of both investigators revealed similar flow characteristics in air for most cases. Slight differences noted by Yin included (1) small tangential oscillations of the vertical plume at some higher temperature differences, (2) some unsteady contractions of the central-eddy region at higher temperature differences, (3) the lack of a stagnant lower region for the smallest diameter ratio and higher temperature differences, and (4) the appearance of a three dimensional spiral flow near the upper vertical axis at the highest temperature differences of the smallest diameter ratio.

A more recent continuation of the spherical enclosure case was conducted by Baughman (5). He investigated air as the gap working fluid but utilized spherical bodies positioned eccentrically above and below the concentric position. These results showed that the eccentric locations affected the flow basically in that there were only geometric distortions of the three basic flow patterns previously reported for the concentric case. Postulations were also made as to the effect of the eccentricities on the mechanisms of heat transfer involved.

Analytical and experimental work has been done in the area of a long rectangular enclosure. Batchelor (9), by expanding a dimensionless temperature and a dimensionless stream function in power series of the Rayleigh number, found an analytical solution considering only two-dimensional flow in a long rectangular enclosure. This rectangular enclosure case, where heat was transferred between the two vertical walls which were at different temperatures, was extended using numerical methods by Davis (10), Wilkes and Churchill (11), and Newell and Schmidt (8). A more complete reference listing appears in Newell and Schmidt. These works, even though they do concern enclosed regions, are not directly applicable to this work in that no internal body was present. Powe, Carley, and Carruth (12)

numerically investigated natural convection in cylindrical annuli.

This literature review covers several pertinent aspects relating to this work. However, no directly relatable references are available concerning the results of this work, that of investigating the natural convection process between a concentrically located isothermal heated spherical inner body and an isothermal cooled cubical enclosure by flow visualization methods.

CHAPTER III

EXPERIMENTAL APPARATUS AND PROCEDURE

EXPERIMENTAL APPARATUS

Use of an isothermal cubical enclosure as the outer configuration for the natural convective flow visualization project at hand required both design and assembly of a new experimental apparatus. The most closely related previous work utilized an isothermal sphere as an enclosure configuration. Based on the successful results obtained by Yin (4) and Baughman (5) with the spherical enclosure, their apparatus was chosen as the basic model for the design and assembly of the apparatus utilizing a cubical enclosure. Several modifications were adapted to this new apparatus and several improved features were incorporated in the design. Figures 3.1, 3.2, and 3.3 show the experimental apparatus, a schematic indicating the relation of the support equipment, and a cutaway drawing of the sphere-cube-jacket arrangement, respectively.

Due to the nonsymmetry caused by having a sphere located within a cubical enclosure, the flow was viewed in (1) a vertical plane perpendicular to a cube face through the sphere's vertical axis, (2) a diagonal vertical plane through the vertical axis of the sphere and oriented at approximately 45° with a cube face, and (3) horizontal planes.

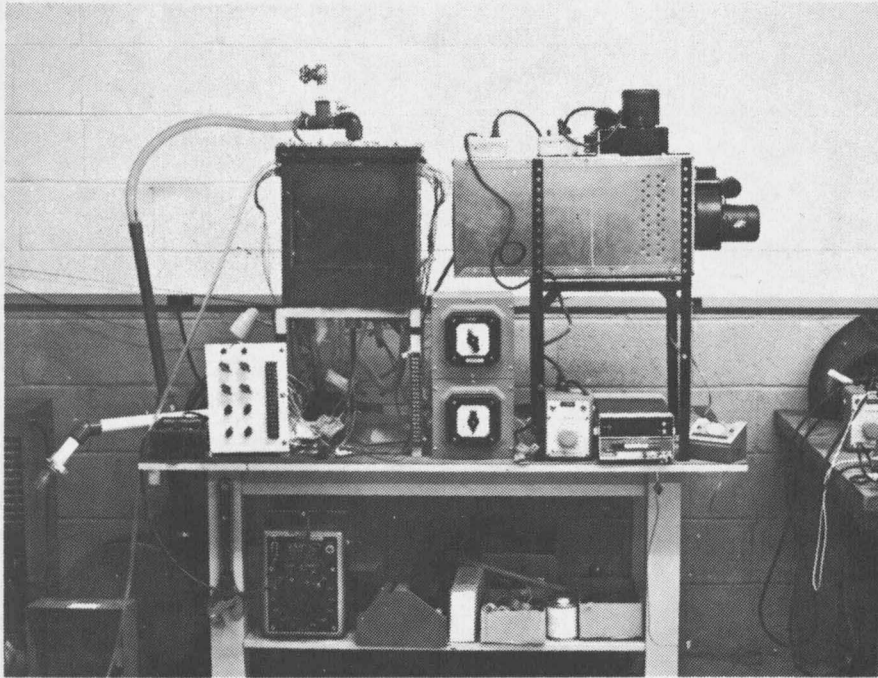


Figure 3.1 Experimental Apparatus

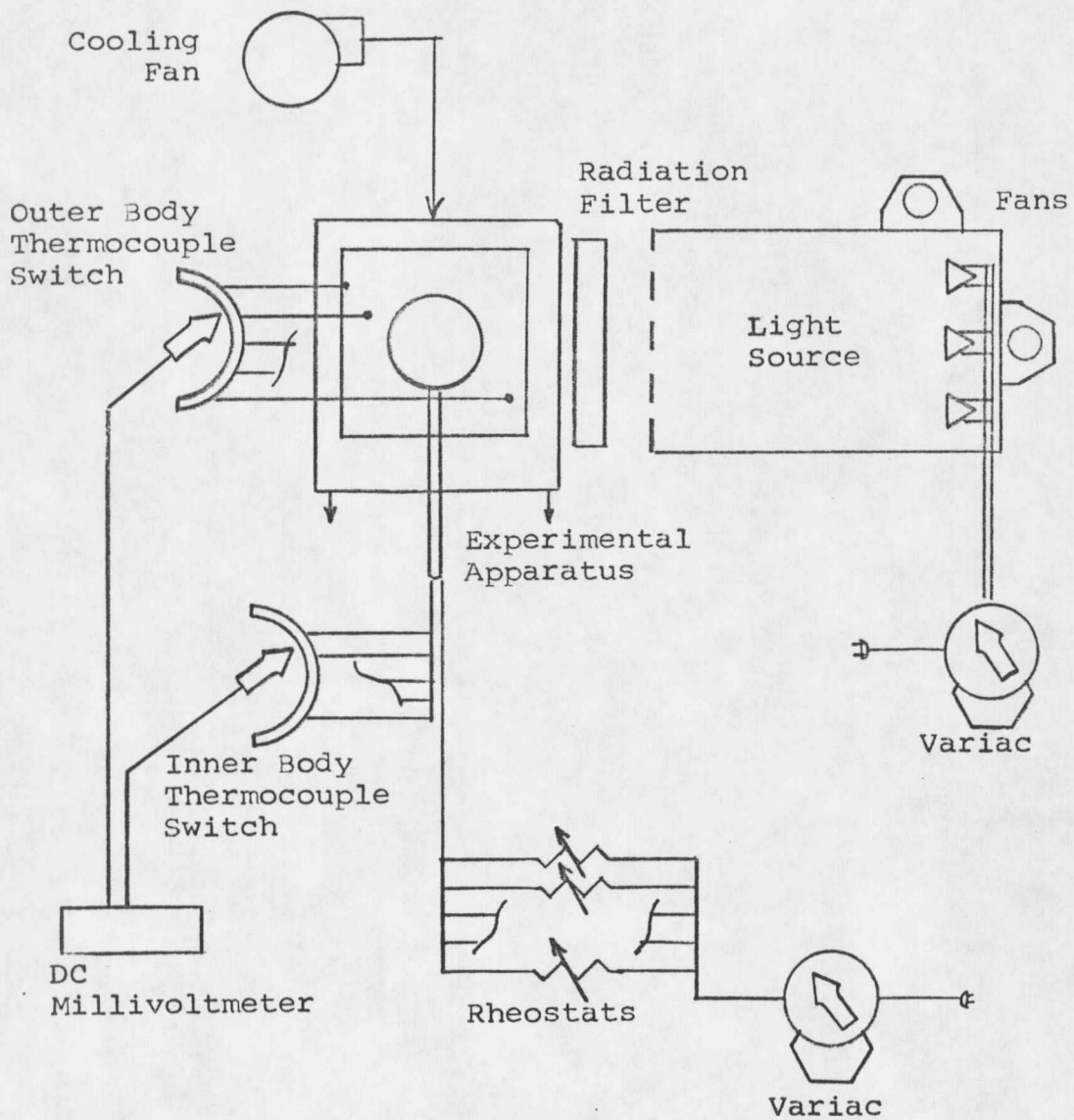


Figure 3.2 Schematic Showing the Support Equipment.

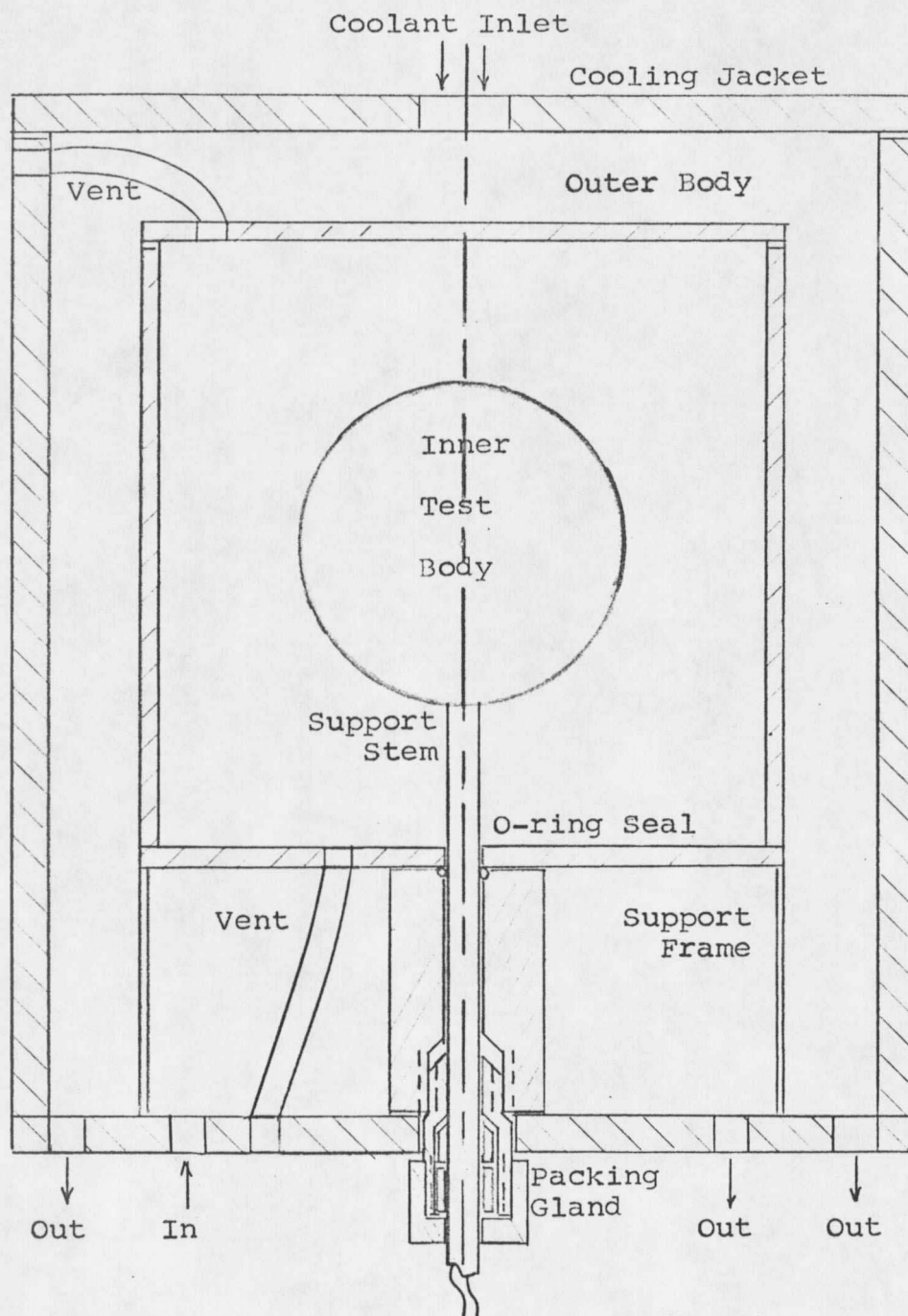


Figure 3.3 Cutaway Drawing of the Sphere-Cube-Jacket Arrangement.

The need for three planes of view stemmed from desiring to investigate any asymmetry of the flow, any three-dimensional flow, and/or the extent of unsteadiness of the flow. Figure 3.4 shows the relation between the view planes investigated.

The cubical outer body was made of sheet Plexiglass with a nominal thickness of 0.25 inches and measured 9.9 inches on an inside edge. Plexiglass met the transparency requirements and allowed for ease of machining and assembly. Machine screws were used to hold the bottom and sides together while a silicone sealant was used during assembly to insure a leakproof container. The top edges were tapped and fitted with studs. Wing nuts allowed for ease of removal of the top while a gasket provided sealing around the top.

In the bottom, a centrally located 0.525 inch hole was drilled to allow passage of the 0.500 inch OD inner body support stem. The inner bodies are described later. In one corner of the top, a vent hole was fashioned to serve a two-fold purpose. It allowed for purging of the cigar smoke during each experimental run with air as the test fluid, and provides a fill vent for use in future studies to be conducted on the apparatus with liquid test fluids. Similar vent holes were located in the bottom of the cube for purposes of introducing the cigar smoke and filling the gap with a test fluid.

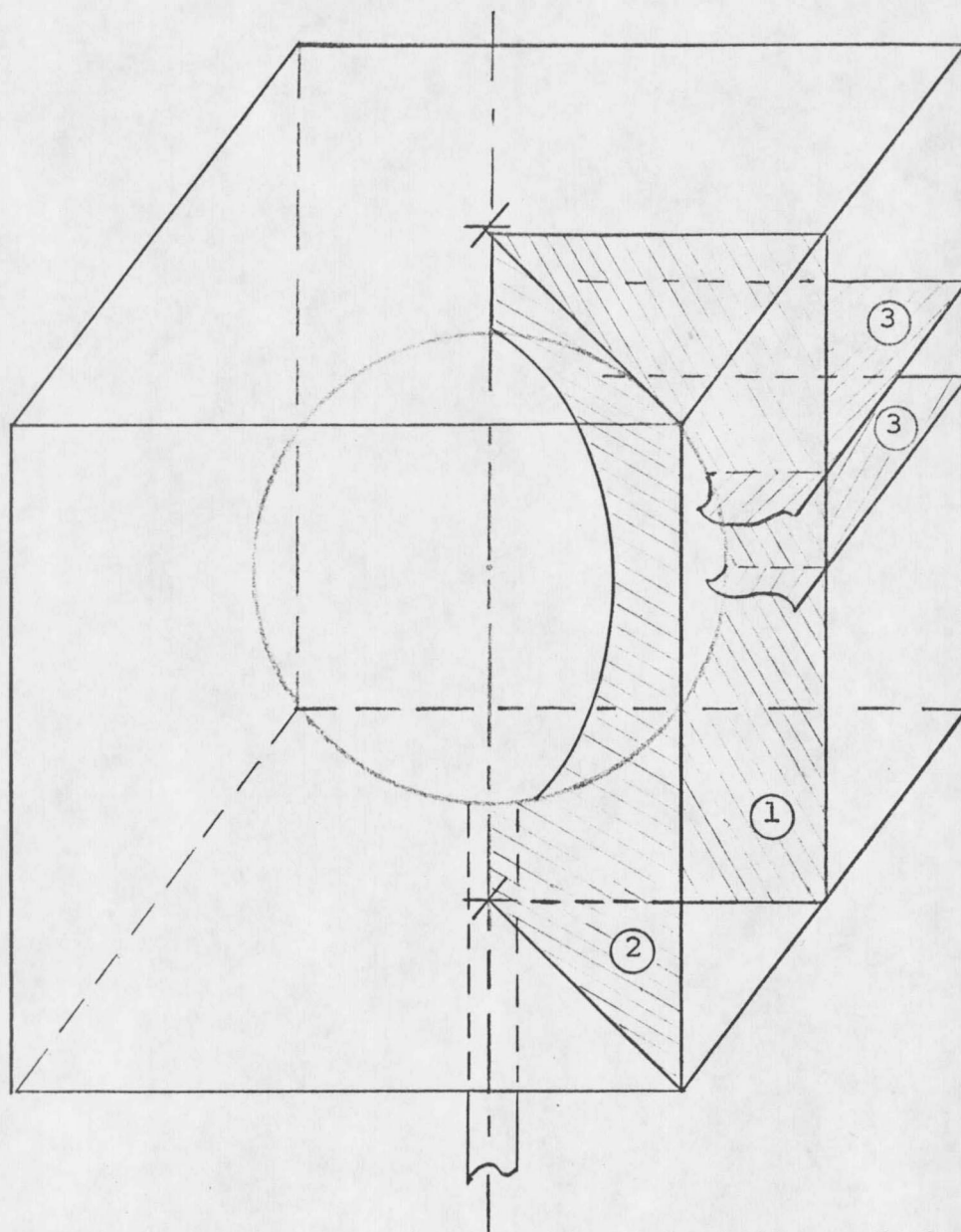


Figure 3.4 Drawing Showing the Orientation of the Planes in which the Flow was Observed.

- ① - Perpendicular Vertical Plane
- ② - Diagonal Vertical Plane
- ③ - Horizontal Planar Sections

At 21 locations on the outer body, copper-constantan thermocouples were placed to monitor the surface temperature on the inside of the cube. Small holes were drilled through the Plexiglass and the thermocouples were epoxied in place, flush with the inside surface.

Surrounding the outer body was a jacket through which a cooling fluid could be circulated. The top, front, and right sides were made of sheet Plexiglass with a 0.500 inch nominal thickness. The bottom and other two sides were made of sheet aluminum. The jacket was held together in a similar fashion to the outer body, with machine screws and a silicone sealant. The top edge was fitted with studs, and wing nuts provided for ease of access to the outer body while a gasket provided the seal.

The cubical outer body was supported around its base by a frame attached both to the outer body and to the cooling jacket. Concentric with the stem hole in the bottom of the outer body was a solid rectangular adaptor with a 0.525 inch hole through it. Fitted between this adaptor and the bottom of the outer body was an O-ring that sealed the stem of the inner body. A $\frac{1}{2}$ " Conax packing gland was used on the outside of the water jacket to provide a backup seal to the aforementioned O-ring and to provide a positive control for positioning and securing the inner body at

the desired vertical location.

The cooling jacket provided containment of the cooling medium utilized in maintaining the outer body in an isothermal condition. With air as the gap working fluid, forced air cooling was used to maintain the outer body isothermal. The coolant entered the jacket via a centrally located inlet duct on the top of the jacket, and impinged directly on the top center of the outer body. The coolant exited via four ducts located in the bottom corners of the jacket. This arrangement provided cooling for the top and sides of the outer body. The bottom portion of the cooling jacket was separated from the main portion by the outer body support frame. A coolant inlet and exit to this lower region allowed for a necessarily different cooling rate along the lower portion of the outer body. Also located in this region immediately beneath the bottom surface of the cube was a 0.25 inch diameter tubular resistance heater, in the event that heating, not cooling, of the bottom of the outer body was required to maintain an isothermal condition. However, it was found that with air as the gap working fluid, stagnant air in this region yielded an isothermal state when coolant was flowing over the other five sides of the outer body.

The five spherical inner bodies used in this

investigation were kept isothermal by use of heating tapes attached to the inner surface of the 0.030 inch thick copper spheres. These tapes, manufactured by Clayborn Labs, Inc., were 0.125 inches wide and consisted of a resistance wire embedded between a metallic insulative foil on one surface and an adhesive compound on the other surface.

The adhesive surface allowed the sections of tapes to adhere to the inner surface of the sphere while being wound spirally around the inside of the sphere. The tapes were spaced at approximately one tape's width apart. Figure 3.5 shows these tapes in a 7.0 inch sphere. Once the tapes were installed, a thin layer of silicone sealant was spread over the entire inner surface to insure adhesion. The number of tapes in each body varied depending on the size of the body. Four tapes were used inside the 3.5 inch sphere and a maximum number of eight tapes was used in the 9.0 inch sphere. Although the length of each segment of tape in a body was somewhat arbitrary, approximate ratios of the lengths were arrived at by assuming a necessary power density relation along a vertical circumference, then trying to approximate this variation by use of the various tape lengths. It was found that this was not an altogether accurate approximation, but when coupled with an exterior power regulation system, the results were quite adequate. Thus, varying the

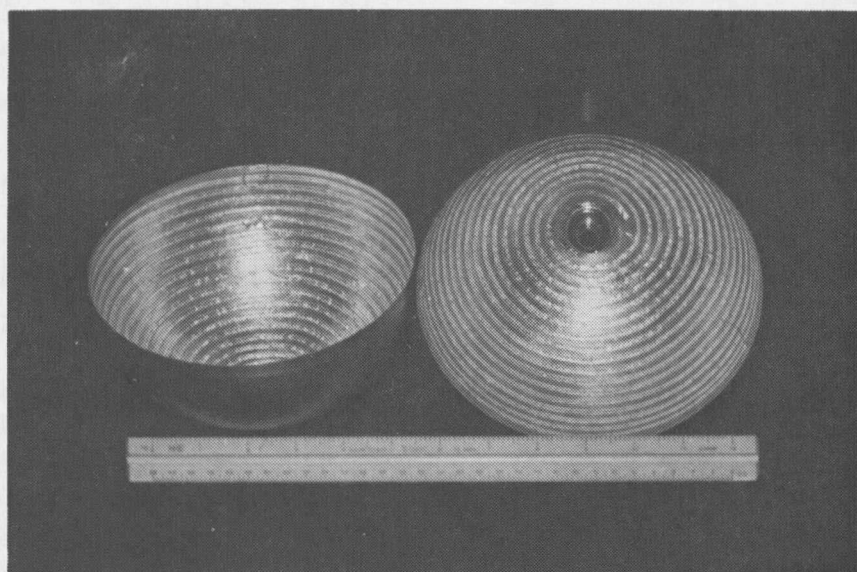


Figure 3.5 Interior of Inner Sphere

power to each tape segment allowed the inner bodies to be kept at an essentially isothermal condition, as discussed later.

Copper-constantan thermocouples were used to monitor the inner body temperatures. Holes were drilled through the copper spheres and the thermocouples were glued in place from the inside of the spheres, flush with the exterior surface. Later, the exterior surface was soldered, filling the thermocouple holes, then filed smooth.

Both the thermocouple leads and the power leads connected to the heating tapes exited the inner body via a 0.500 inch OD stainless steel tube soldered to the base of the copper sphere. In addition, this stem supplied a means of support of the inner body when in position within the cubical outer body.

After checking for continuity of all tapes and thermocouples, final assembly of the inner test bodies involved stuffing the two hemispherical halves with a fiberglass wool insulative material and soldering the two completed halves together. The fiberglass material served the purpose of minimizing any internal convective activity.

The foregoing describes the main experimental apparatus. Following is a brief description of the support equipment.

Forced air cooling was provided by a 30 cfm fan. It was not necessary to attempt to control the cooling air temperature since a desired temperature difference could be obtained by adjusting only the inner body's surface temperature.

The main power supply was an AC Variac autotransformer. This supply was connected to a control panel consisting of eight 10-ohm single-turn rheostats. Thus with the main Variac voltage setting fixed and a variable resistance in series with each tape, the power produced by each tape could be regulated by use of the rheostats.

Temperature monitoring was by use of Honeywell 24 point thermocouple switches and a Digitec DC millivoltmeter manufactured by United System Corporation. The temperatures were recorded as millivolt readings and later converted to degrees by the data reduction computer program.

A light source consisting of three 300-watt (3400°K) home movie lights and simple reflection system provided an approximately collimated beam of light which then passed through three 0.25 inch slits, thus allowing planar views of the flow region under investigation. A calumet 4" x 5" professional camera and Tri-X Pan professional film was used for photographs.

EXPERIMENTAL PROCEDURE

The inner body to be investigated was placed in the apparatus after having been painted flat black to reduce unnecessary reflections. After the outer body and jacket tops were replaced, the cooling fan was started and cigar smoke was injected slowly into the gap. A visual check was made for any disturbances of the working fluid which might be caused by a poor seal of the gasket around the top of the outer body. When no disturbances were noted, the inner body was centrally positioned by marking the stem at the maximum upper position and the maximum lower position of the inner body and securing the stem with the packing gland at the midpoint of the two marks. With the body positioned at the correct vertical position, the power leads were connected to the control panel and the thermocouple leads connected to the switch box.

With the cooling system operating, the power to the heating tapes was set, and time was allowed for a steady state to be reached. The inner body thermocouple readings were checked. If an isothermal condition did not exist, the control rheostats were adjusted in an appropriate manner and time allowed to reach a new equilibrium. Once the inner body became isothermal at an equilibrium state, investigation of the flow region was conducted.

Cigar smoke, used to provide tracer particles with air as the test fluid, was injected into the gap. Care was used in this injection as not to unnecessarily disturb the flow conditions. With the light source positioned so the desired viewing plane was illuminated, the flow characterizations were noted and/or photographs taken. A short time was required for the smoke to be distributed in the flow field. However, the time available for each investigation of the flow was limited to the time it took for the cigar smoke to be diffused such that flowlines could no longer be distinguished.

After each planar investigation, the gap was purged. Before another viewing could be made, equilibrium again had to be reached.

This procedure was repeated as many times as were required to adequately describe the flow. The data recorded for each run included:

- 1) inner body thermocouple readings - mv,
 - 2) outer body thermocouple readings - mv,
 - 3) atmospheric pressure - inches of mercury,
- and 4) power control rheostat settings, % of full value.
- Other pertinent data recorded were the run number, the total wattage to the tapes, the inner body size, the time, the date, and the plane being investigated.

CHAPTER IV

EXPERIMENTAL RESULTS

The experimental results are presented in two sections. The first section includes the qualitative discussions of the flow patterns that were observed and photographed for each of the five spherical inner body sizes. This section contains a subsection for each different inner body size wherein individual characteristics are noted. The second section is a summary of the experimental results. Similarities and dissimilarities of the characteristics of the five bodies are noted, and pertinent discussions are presented. However, before the results are presented, several points should be discussed.

As previously noted, with air as the gap working fluid, cigar smoke was used as the tracer particles. Generally, the smoke particles yielded satisfactory results. However, in some cases, the cigar smoke was a poor flow indicator. At low temperature differences, the cigar smoke particles seemed too heavy to be carried into the slow moving regions of the flow. In the faster flow regions, the smoke would diffuse to the point where no flowlines were visible, while in the slow moving regions no smoke was yet evident. Conversely, at high temperature differences when the fluid velocities were large throughout most of the flow field,

the smoke would diffuse to the point where the flow became indistinguishable in a very short time.

The properties of the air in the gap were considered temperature dependent. The temperature at which these properties were determined was the arithmetic mean temperature of the inner and outer bodies. This mean temperature was defined as

$$T_{am} = (T_{i,ave} + T_{o,ave})/2. \quad (4.1)$$

A note on the error involved in the assumption of isothermality of the outer body is appropriate. Upper and lower limits on the impressed temperature difference were dependent on being able to keep the outer body isothermal. At low temperature differences, small temperature variations on the outer body resulted in large percent deviations of the temperature difference between the inner test body and the outer body. A percent deviation was defined as the absolute value of the difference between the local outer body temperatures and the average outer body temperature divided by the difference between the average inner body temperature and the average outer body temperature, or

$$Dev = \frac{|T_l - T_{o,ave}|}{(T_{i,ave} - T_{o,ave})} \times 100. \quad (4.2)$$

The lower and upper limits of the temperature difference

were chosen so that the maximum deviation would be 20%. In general, though, this deviation was less than 10% for most of the presented results. The upper limit was also set by another factor. This investigator felt that the upper limit on the temperature difference between the inner body and the outer body that could be reached was when the outer body could not be kept below 120°F. This was based on what was felt to be the limitations of the Plexiglass material of the outer body.

In the flow pattern descriptions that follow, the characteristic dimension used in calculating the Grashof number (equation 2.1) was defined as one-half the difference between the length of the side of the cubical outer body and the inner body's diameter. This characteristic dimension will hereafter be referred to as the gap width. The temperature difference used in calculating the Grashof number was the difference between the average inner body temperature and the average outer body temperature.

It should be noted that a difficulty arises in interpreting the flow in the horizontal sections through the flow patterns. At the horizontal sections investigated, the major flow movement was in the vertical direction. Consequently, flow movement parallel to the horizontal sections was nearly indistinguishable. Thus it was felt, in most

cases, descriptive analysis of the horizontal plane sections was limited to discussion of apparent symmetry and, in only a few cases, to noting major aspects of three dimensional flows.

Due to the amount of calculations that had to be made for each flow case, a computer program was utilized. This program is listed in the Appendix and was written for and run on a Xerox Data Systems Sigma 7 digital computer.

FLOW PATTERN DESCRIPTIONS

3.5 INCH SPHERE

The first sphere-cube arrangement investigated was a 3.5 inch sphere located concentrically in a 9.9 inch cube, with a gap width of 3.2 inches. The temperature differences investigated were from $\Delta T = 24^{\circ}\text{F}$ ($N_{Gr} = 626,000$) to $\Delta T = 115^{\circ}\text{F}$ ($N_{Gr} = 2,042,000$).

The flow pattern observed in the vertical plane perpendicular to a cube side for the lowest temperature difference is shown in Figure 4.1. (Figure 3.4 shows the orientations of the planes of view investigated.) Evident in the flow pattern are the three flow regions that appeared in nearly all of the flow cases investigated in the perpendicular vertical plane. These regions are: (1) a relatively high velocity region that basically followed the geometric

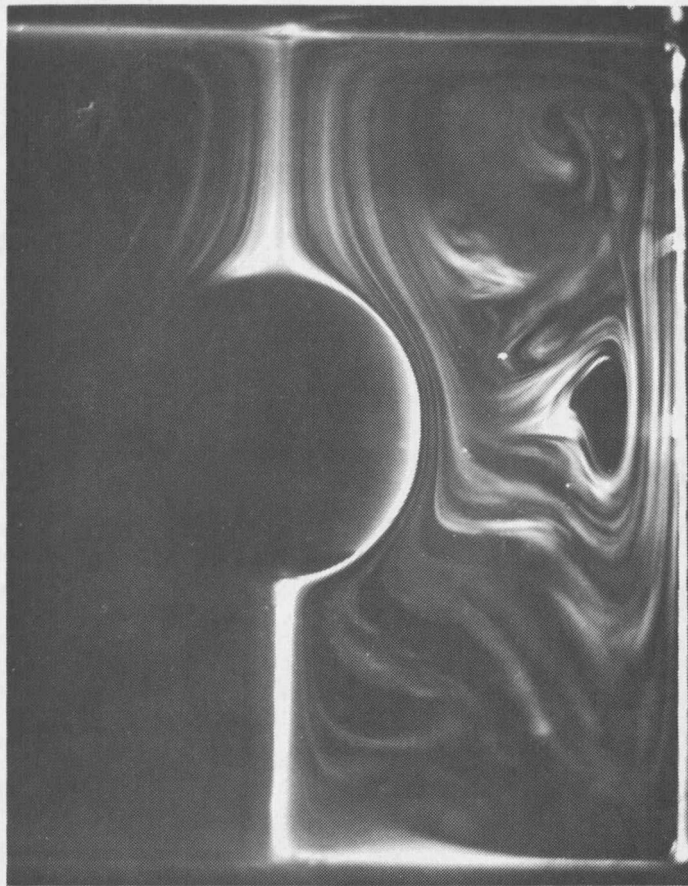


Figure 4.1 Flow Pattern in the Perpendicular Vertical Plane for

ID = 3.5 inches

$\Delta T = 24^{\circ}\text{F}$

$N_{\text{Gr}} = 626,000$

configuration of the solid boundaries, (2) an upper central region that was characterized by at least one interior corner eddy type flow and usually a slight amount of three dimensional effects, and (3) a lower region characterized by relatively slow moving fluid and, oftentimes, a small amount of three-dimensional flow. The individual characterizations of each region are discussed in more detail for each flow discussed hereafter.

As evident in Figure 4.1, the high speed region follows the contour of the solid boundaries. A steady, vertical plume appears along the upward vertical axis as the upward flow leaves the inner sphere. The plume visually separates the flow into two portions in the plane, indicating axisymmetry. The downward fluid flow along the cube side, as it is cooled, separates from the surface and begins a slow drift in the lower region toward the inner sphere. In the upper central region, a single eddy is evident in the upper corner. Also in the upper region, some three-dimensional effects are present. This was the only case investigated where a seemingly void space (at the midplane) appeared in the flow pattern. Higher temperature differences and different size inner bodies did not yield such a void space. It would be unreasonable to assume this space were completely stagnant. Possibly, it is a very slow eddy or spiral

motion into which no smoke enters.

The flow in the diagonal vertical plane appears in Figure 4.2, which is for $\Delta T = 33^{\circ}\text{F}$ ($N_{Gr} = 758,000$). The diagonal flow pattern shown is representative of the patterns encountered for all the diagonal observations with this inner body. The flow consists of high speed fluid following the upper boundaries, an interior corner eddy in the upper region, a hump type flow between the cube's edge and the sphere, and slow fluid mixing in the lower region.

Observations of horizontal planes at low temperature differences showed the flow to be symmetric with respect to both the vertical perpendicular plane and the vertical diagonal plane. These observations verified the minor three-dimensional flow which appeared in the upper central region of the perpendicular plane.

The flow pattern at the upper limit of the temperature difference investigated appears in Figure 4.3. Evident in the photograph are the three regions previously noted as common to this perpendicular vertical view plane. The vertical plume separates the flow along the upward vertical axis. The high speed fluid flows upward, around the inner sphere, across the top, and down the side. At about the midplane, the high speed flow separates from the wall. This separation was first evident at $\Delta T = 51^{\circ}\text{F}$ ($N_{Gr} =$

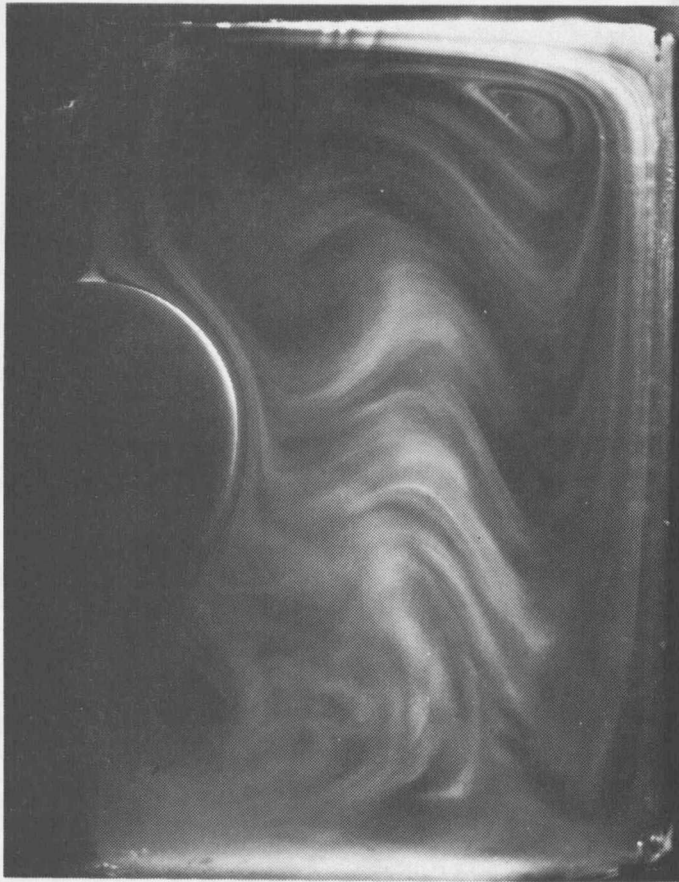


Figure 4.2 Flow Pattern in the Diagonal Vertical Plane for

ID = 3.5 inches

$\Delta T = 33^{\circ}\text{F}$

$N_{Gr} = 758,000$

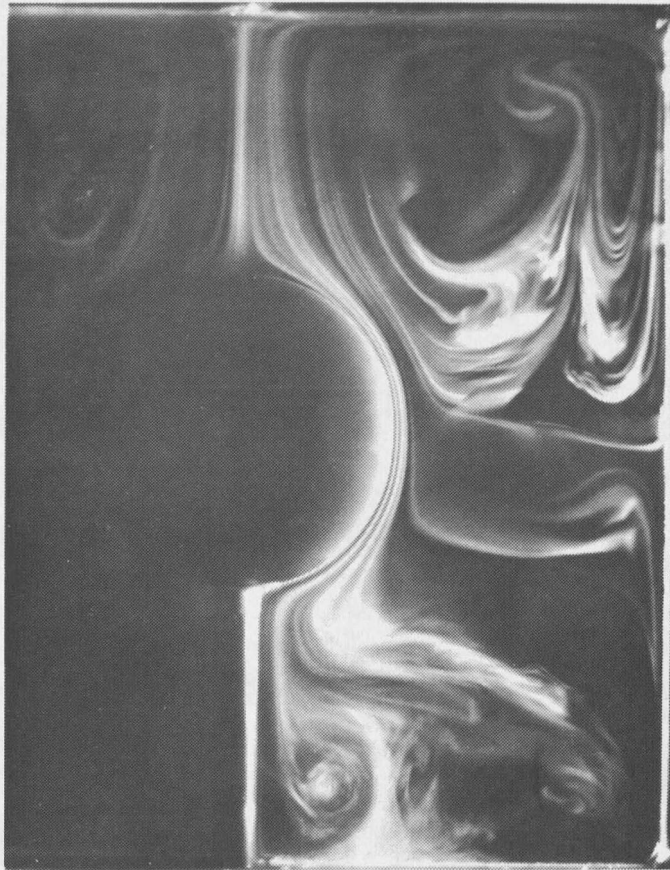


Figure 4.3 Flow Pattern in the Perpendicular Vertical Plane for

ID = 3.5 inches

$\Delta T = 113^{\circ}\text{F}$

$N_{\text{Gr}} = 1,862,000$

1,101,000). The point of separation was about 30° below the horizontal line through the sphere's center for $\Delta T = 51^\circ\text{F}$. The point of separation moved up the cube's side with increased temperature differences to the midplane point at $\Delta T = 113^\circ\text{F}$. The interior corner eddy increased in size, but its central position did not appear to change position significantly with increased temperature difference. Comparison of Figures 4.1 and 4.3 shows a more pronounced upward flow in the upper interior region with the larger temperature difference. Much more three-dimensional flow was also evident at the higher temperature differences in both the upper central region and the lower region. The flow at the highest temperature difference investigated, $\Delta T = 115^\circ\text{F}$, seemed to be near the point of going unsteady; however, for all the temperature differences investigated, except for some minor three-dimensional flows, the patterns appeared steady with time.

The diagonal vertical plane observations, up to the maximum temperature differences investigated, revealed flow very similar to that at the low temperature difference, as shown in Figure 4.2. Two minor pattern variations were noted, and these both seemed temperature-difference dependent. The interior corner eddy flow grew in size with increased temperature difference, but its central position

was invariant. The lower mixing region previously noted, developed into a pair of counter rotating vortices that resembled slow spiral motion indicating three-dimensional flow. Figure 4.4 shows a typical flow pattern in the horizontal midplane from which symmetry of the flow was deduced.

Several similarities were noted between the flow patterns observed in the perpendicular vertical plane and the diagonal vertical plane. Compare, for example, Figures 4.2 and 4.3. High speed flow followed the geometric contour in the upper portion of each plane. A temperature-difference dependent separation of the downward flow along the cube's side occurred in the perpendicular vertical plane, whereas no separation occurred in the corresponding downward flow in the diagonal vertical plane. In the upper central region of both planes, an interior corner eddy occurred. Both the eddy's shape and central position were different in each of the two planes. The flow in the lower region was similar for both planes, but the flow in the upper central region was significantly different.

4.5 INCH SPHERE

The second geometric configuration investigated was a 4.5 inch diameter sphere located concentrically within the 9.9 inch cube. The gap width was 2.7 inches. The



Figure 4.4 Flow Pattern in the Horizontal Midplane for

ID = 3.5 inches

$\Delta T = 108^{\circ}\text{F}$

$N_{Gr} = 1,828,000$

temperature differences investigated were from $\Delta T = 15^{\circ}\text{F}$ ($N_{\text{Gr}} = 253,000$) to $\Delta T = 91^{\circ}\text{F}$ ($N_{\text{Gr}} = 1,030,000$).

Shown in Figure 4.5 is the flow pattern for $\Delta T = 30^{\circ}\text{F}$. It is representative of the flow in the perpendicular vertical plane for all the temperature differences investigated. A high speed flow follows the contour of the boundaries, upward around the sphere forming a vertical plume around the upward vertical central axis, across the top, and down the side to a point of separation. The point of separation was at an angle of about 30° below the midplane for the lowest temperature difference, $\Delta T = 15^{\circ}\text{F}$, and moved upward as the impressed temperature difference increased. At the maximum temperature difference investigated, $\Delta T = 91^{\circ}\text{F}$, the point of separation was just slightly below the midplane.

The upper interior region was characterized by an interior corner eddy as with the 3.5 inch sphere. The eddy size increased with increased temperature difference, but its central position and shape did not vary noticeably. The upper central region also contained counter-rotating cells. These cells were not very distinct for the low temperature differences investigated, but became very noticeable near the upper limit. Three-dimensional effects apparent in the upper central region seemed to be of a spiral vortex type.

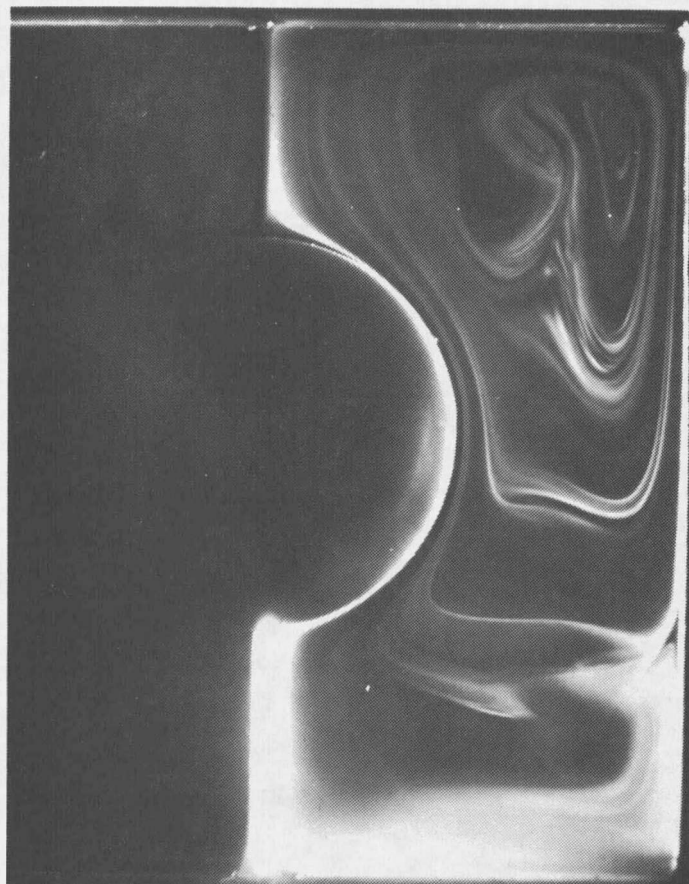


Figure 4.5 Flow Pattern in the Perpendicular Vertical Plane for

ID = 4.5 inches

$\Delta T = 30^{\circ}\text{F}$

$N_{Gr} = 447,000$

The lower region at the lower temperature differences was almost stagnant. Fluid was drawn upward around the sphere from this lower region, which led to the assumption that some slow three-dimensional flow existed in the lower region to satisfy continuity. At moderate to high temperature differences, this three-dimensional effect became very noticeable. However, the onset of these three-dimensional flows could not be fixed at a specific temperature difference.

In the diagonal vertical plane, Figure 4.6, the high speed flow followed the geometric boundary, as with the 3.5 inch sphere. No separation of the flow occurred in the downward flow along the edge of the cube. Instead, the flow peeled off gradually along the whole of the downward flow region, and drifted towards the inner sphere. This drifting fluid moved upward, then downward, in a hump pattern as it approached the inner sphere. The point at which the flow reached the maximum height in the hump formed a vertical line located approximately one-third the diagonal gap distance between the sphere and the cube edge. The location of this line did not seem to vary significantly at different temperature differences.

The size of the interior corner eddy that appeared in the upper central region increased with an increase in

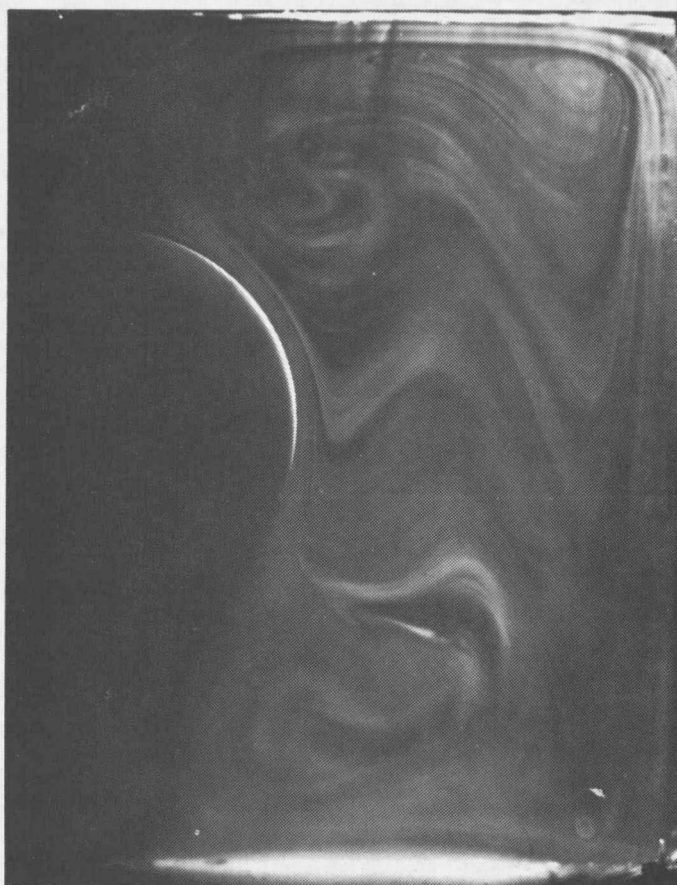


Figure 4.6 Flow Pattern in the Diagonal Vertical Plane for

ID = 4.5 inches

$\Delta T = 89^{\circ}\text{F}$

$N_{\text{Gr}} = 920,000$

temperature difference. However, its central position did not seem to change. Also in the upper central region, a gradual increase in the three-dimensional flow near the plume section with increased temperature difference was noted. This flow appeared to be similar to counter rotating vortices in a spiral configuration. A similar flow occurred in the lower region. However, in the lower region, the three-dimensional spiral flow was much slower than that in the upper central region. Figure 4.6 shows a typical diagonal pattern near the upper limit of the temperature differences investigated.

The similarities noted for the 3.5 inch sphere are applicable for the 4.5 inch sphere.

5.5 INCH SPHERE

The third geometric configuration investigated was a 5.5 inch diameter inner sphere located concentrically in a 9.9 inch cube. The gap width was 2.2 inches. The temperature differences investigated ranged from $\Delta T = 28^{\circ}\text{F}$ ($N_{\text{Gr}} = 206,000$) to $\Delta T = 97^{\circ}\text{F}$ ($N_{\text{Gr}} = 523,000$).

The steady flow that appeared in the perpendicular vertical plane for the temperature difference of 28°F is shown in Figure 4.7. The pattern shown is typical of the observed flow in this plane up to a temperature difference of 61°F . Above $\Delta T = 61^{\circ}\text{F}$ ($N_{\text{Gr}} = 391,000$), a periodic unsteady flow

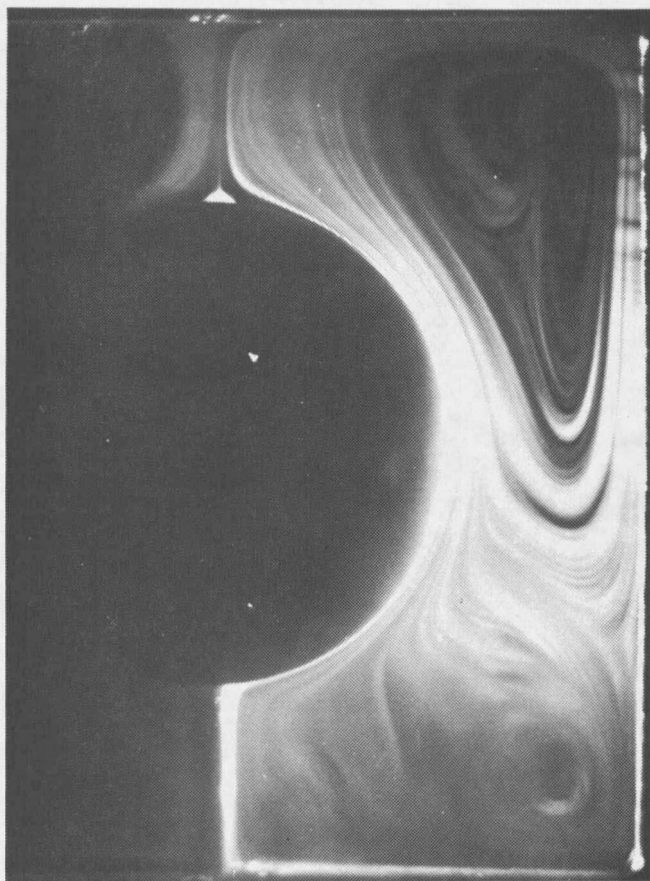


Figure 4.7 Flow Pattern in the Perpendicular Vertical Plane for

ID = 5.5 inches

$\Delta T = 28^{\circ}\text{F}$

$N_{\text{Gr}} = 206.000$

occurred in a portion of the gap. The pattern appearing in Figure 4.7 is similar in several respects to the flows observed and previously noted for the 3.5 inch and the 4.5 inch spherical inner bodies in the perpendicular vertical plane. The similarities are in the existence of the high speed flow following the contour of the solid boundaries, an interior corner eddy in the upper central region, a temperature-difference dependent separation from the wall of the downward flow along the cube's side, and a relatively slowly moving fluid in the lower region. However, distinct differences were also observed for the 5.5 inch spherical inner body.

Three-dimensional flows were evident at all the temperature differences in the lower region. The flow in the lower region of the gap was very slow for the lower temperature differences investigated. The mixing movement increased in magnitude as the temperature difference was increased. The eddy motion evident in the lower corner of Figure 4.7 was common to all the patterns observed in this plane. As the impressed temperature difference was increased, this eddy motion became very evident as a spiral type motion. At the highest temperature difference investigated, $\Delta T = 97^{\circ}\text{F}$, it had become a pronounced unsteady spiral motion. At this high temperature difference, the flow in the entire

lower region was characterized by a rather violent mixing motion.

Fluid was drawn from the lower region into the high speed flow upward around the sphere. The three-dimensional flow in the lower region was effectively damped out as it entered the high speed boundary flow. The high speed fluid flow upward around the sphere consisted of both the lower region fluid and fluid that had separated from the outer wall and drifted radially inward. The thickness of this high speed flow around the inner body did not appear to be temperature-difference dependent. Neither did the width of the axisymmetric plume that formed around the upper central vertical axis as the fluid separated from the inner body.

The high speed flow down the side of the outer body began separating near the midplane and flowing radially inward towards the inner body. At the lowest temperature difference, $\Delta T = 28^{\circ}\text{F}$, the downward flow separated from the wall at an angle of about 25° below the midplane. The separation point was at an angle of about 15° below the midplane at the highest temperature difference, $\Delta T = 97^{\circ}\text{F}$. The separation point was in all cases steady with time.

Figure 4.8 shows the upper central region for $\Delta T = 28^{\circ}\text{F}$. Evident from the photograph is, not a closed eddy



Figure 4.8 Flow Pattern in the Upper Central Region of the Perpendicular Vertical Plane for

ID = 5.5 inches

$\Delta T = 28^{\circ}\text{F}$

$N_{Gr} = 206,000$

formation, but a three-dimensional spiral eddy formation. The spiral is fed at the top by two distinguishable flows. The first is an upward flow that splits the central region. The second is a three-dimensional flow that enters the central region at the upper left of the spiral. At $\Delta T = 28^{\circ}\text{F}$, the spiral was fed by steady flows. At $\Delta T = 61^{\circ}\text{F}$, the same basic flow shown in Figure 4.8 was present but the flow feeding the spiral had become unsteady causing the spiral to become unsteady. The inverted "V" that split the central region would form and collapse periodically. The period was about 6 seconds. This periodic formation caused a periodic contraction and expansion type disruption of the spiral. However, no other portion of the flow outside the central region was affected by the pulsating spiral. This same pulsating flow in the upper central region was noted up to the maximum temperature difference investigated ($\Delta T = 97^{\circ}\text{F}$). The period of the flow pulsation reduced to about 3 seconds at the highest temperature difference.

Figure 4.9 shows the basic pattern observed for all the temperature differences investigated in the diagonal vertical plane. The pattern is characterized by the same flows that appeared in the diagonal vertical plane as reported for the 3.5 inch and 4.5 inch spheres. There



Figure 4.9 Flow Pattern in the Diagonal Vertical Plane for

ID = 5.5 inches

$\Delta T = 29^{\circ}\text{F}$

$N_{\text{Gr}} = 229,000$

existed a high speed flow which followed the solid boundaries, an upper interior corner eddy, and a hump shaped radial drift towards the inner body. No separation of the downward flow was evident and no lower corner eddy flow was noted for any of the temperature differences investigated as previously reported for the perpendicular vertical plane.

Above $\Delta T = 78^{\circ}\text{F}$ ($N_{Gr} = 491,000$) an unsteady flow was noted in the diagonal vertical plane. The upper interior corner eddy showed a nonperiodic pulsation. Also, the hump formed by the radial drift rose and fell, but no definite period was noticeable. It seemed that the periodic pulsating flow in the perpendicular vertical plane was affecting the diagonal vertical plane flow.

A horizontal plane section is shown in Figure 4.10 for $\Delta T = 29^{\circ}\text{F}$. Evident in the photograph is that the flow is symmetric with respect to the diagonal vertical plane. The flow was also symmetric with respect to the perpendicular vertical plane, though it is not as evident from the photograph. As the impressed temperature difference was increased, the flow in the horizontal sections showed that the three-dimensional flows were indeed steady at the lower temperature differences, but at moderate to high temperature differences, unsteady flows appeared, verifying the patterns



Figure 4.10 Flow Pattern in the Horizontal Midplane for

ID = 5.5 inches

$\Delta T = 29^{\circ}\text{F}$

$N_{Gr} = 227,000$

previously noted in the perpendicular and the diagonal vertical planes.

7.0 INCH SPHERE

The fourth geometric configuration investigated was the gap between a 7.0 inch spherical inner body and a 9.9 inch cubical outer body. The gap width was 1.45 inches. The temperature differences investigated (for which the deviation in the assumed isothermal condition, defined by equation 4.2, was less than 20%) ranged from $\Delta T = 13^{\circ}\text{F}$ ($N_{Gr} = 31,400$) to $\Delta T = 39^{\circ}\text{F}$ ($N_{Gr} = 81,900$). At $\Delta T = 39^{\circ}\text{F}$, the flow was noted to be very unsteady and investigation of higher temperature differences was felt unnecessary.

At the low temperature difference of $\Delta T = 13^{\circ}\text{F}$, the flow was unsteady, which is described in the discussion following. The photographing of a flow required at least a 2 second exposure due to the low intensity of the light reflection from the cigar smoke tracer particles. Consequently, obtaining a descriptive photograph of the unsteady flow was impossible. In order that the descriptive analysis of the flow in the gap which follows be more meaningful, the photographs presented in Figures 4.11, 4.12, and 4.13 are for temperature differences less than the lower limit (based on the maximum allowable error of 20%) of $\Delta T = 13^{\circ}\text{F}$. The

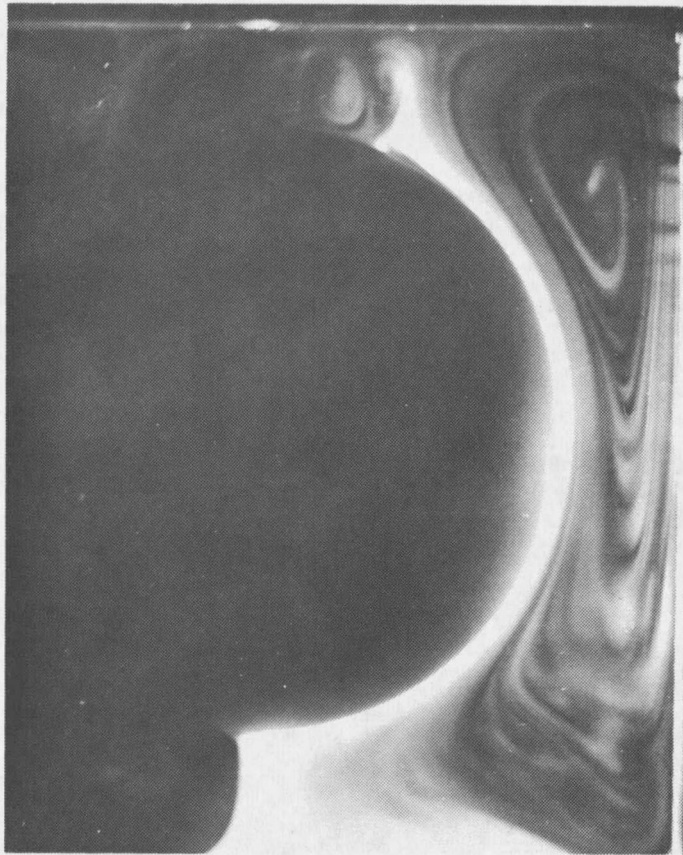


Figure 4.11 Flow Pattern in the Perpendicular Vertical Plane for

ID = 7.0 inches

$\Delta T = 9^{\circ}\text{F}$ (error = 41%)

$N_{\text{Gr}} = 21,800$

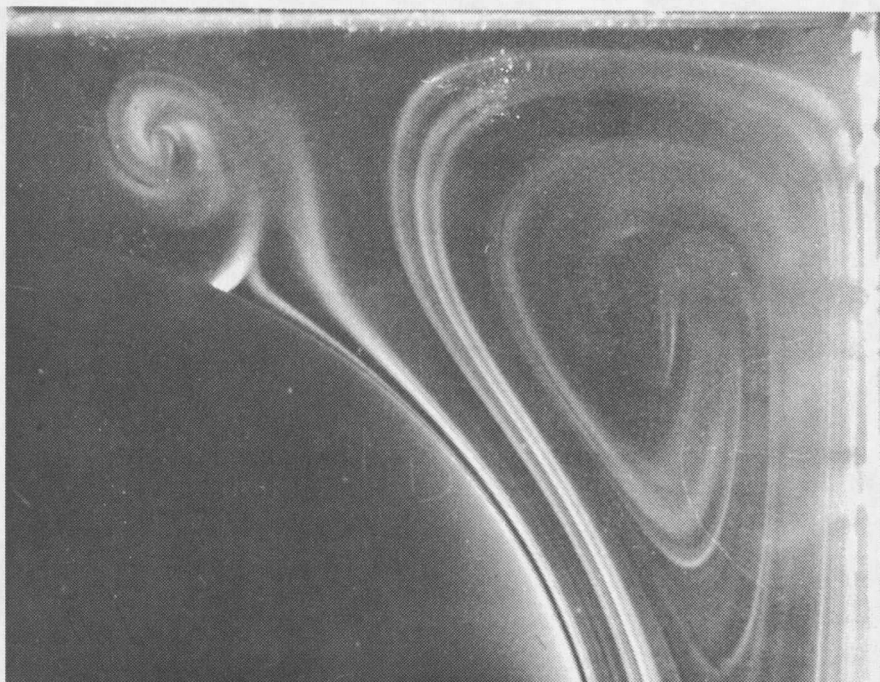


Figure 4.12 Flow Separation From the Inner Body
in the Perpendicular Vertical Plane for

ID = 7.0 inches

$\Delta T = 9^{\circ}\text{F}$ (error = 41%)

$N_{\text{Gr}} = 21,800$



Figure 4.13 Flow Pattern in the Diagonal Vertical Plane for

ID = 7.0 inches

$\Delta T = 10^{\circ}\text{F}$ (error = 30%)

$N_{\text{Gr}} = 27,200$

fluid flow pattern in each of the figures was steady enough to yield describable photographs and basically typical of the unsteady pattern. Included with each figure is the error that corresponds to that particular case.

As previously noted, at the lower limit of the temperature difference investigated, $\Delta T = 13^{\circ}\text{F}$, the flow in the perpendicular and diagonal vertical planes was unsteady. With respect to Figure 4.11, a high speed upward flow existed near the inner body. This flow separated from the inner body at an angle of about 20° measured downward from the upward vertical central axis. Figure 4.12 shows the separation in more detail. The separated flow was divided between the central axis region and the upper central interior region. Flow along the top of the gap and down the side completed an eddy formation encompassing the whole of the upper central region. The point of separation from the inner body acted as a hinge to the separated flow. The separated upward flow oscillated around the 20° angle previously mentioned. This oscillation was nonperiodic. In the region between the oscillating separation line and the upper vertical central axis, a counter-rotating spiral formation appeared which was also unsteady. This spiral grew in size as the separation line moved outward. Then the whole spiral would move, while still rotating, across the top of the gap and

down the side. This slug of fluid decreased in size as it moved outward and downward, causing the whole of the upper central region eddy to be disturbed momentarily. After the disturbance died out, the whole process would at a later time repeat itself.

The whole process of the disturbance was noted to be nonperiodic. This may be plausibly explained. It could not be determined if the spiral motion occurring in the upper axial region was or was not formed in a symmetric manner. Consequently, the slug of rotating fluid that was noted to leave the upper axial region and enter the upper central region nonperiodically may have been a random motion that could occur in any of the vertical planes through the vertical central axis. This explanation is supported by the fact that a very similar nonperiodic disturbance was noted in the diagonal vertical plane, as well as in the perpendicular vertical plane.

Figure 4.13 shows the basic nonsteady pattern observed in the diagonal vertical plane. This diagonal vertical plane pattern was noted to be very similar in several respects to diagonal vertical plane observations for the smaller inner bodies. Similarities exist in the high speed region around the boundary, one large interior corner eddy, no fluid separation in the downward flow along the cube's

edge, and a slow radial drift towards the inner body. Several differences were also noted. There existed no hump type form in the radial drift, only a combined inward and upward flow. The fluid was noted to separate from the inner body similarly to the aforementioned separation in the perpendicular vertical plane observations. Nonperiodically, the whole of the pattern was disturbed by a rotating slug of fluid that emerged from the upper central axis region and moved along the top of the gap and down the side. In all, the flow in the diagonal vertical plane was very similar to that in the aforementioned perpendicular vertical plane.

The similarity of the flow in the perpendicular and diagonal vertical planes with the 7.0 inch inner body is in contrast to the significantly different flows that appeared in each of the perpendicular and diagonal vertical planes in the previously reported smaller inner body configurations. However, the major difference between the 7.0 inch inner body and those previously reported smaller bodies is the unsteadiness that existed at all temperature differences investigated.

The unsteadiness that occurred for the 7.0 inch inner body was temperature-difference dependent. As the impressed temperature difference was increased, the degree of

unsteadiness increased. At the upper limit investigated, $\Delta T = 39^{\circ}\text{F}$, the occurrence of a slug of fluid leaving the central axis region was so rapid, the effects of the previous disturbance had not yet damped out. Thus, investigation of temperature differences above $\Delta T = 39^{\circ}\text{F}$ was felt unnecessary.

9.0 INCH SPHERE

The fifth and last geometric configuration investigated was the gap between a 9.0 inch spherical inner body and a 9.9 inch cubical enclosure. The gap width was 0.45 inches. The temperature differences investigated were from $\Delta T = 13^{\circ}\text{F}$ ($N_{Gr} = 960$) to $\Delta T = 32^{\circ}\text{F}$ ($N_{Gr} = 2,260$). The lower limit was determined by the maximum allowable percent deviation from the assumed isothermal condition of the outer body, and at the upper limit, the flow was unsteady to such large degree that further investigations were felt unnecessary.

As can be seen in Figures 4.14 and 4.15, at the low temperature difference of $\Delta T = 14^{\circ}\text{F}$, the flow in the perpendicular vertical plane was divided by the close proximity of the sphere and the outer body's side at the midplane into two distinct flow regions. The lower region, below the midplane, was characterized by a three-dimensional spiral formation which rotated clockwise. The spiral was bounded on two sides by the outer body's side and bottom and on the third

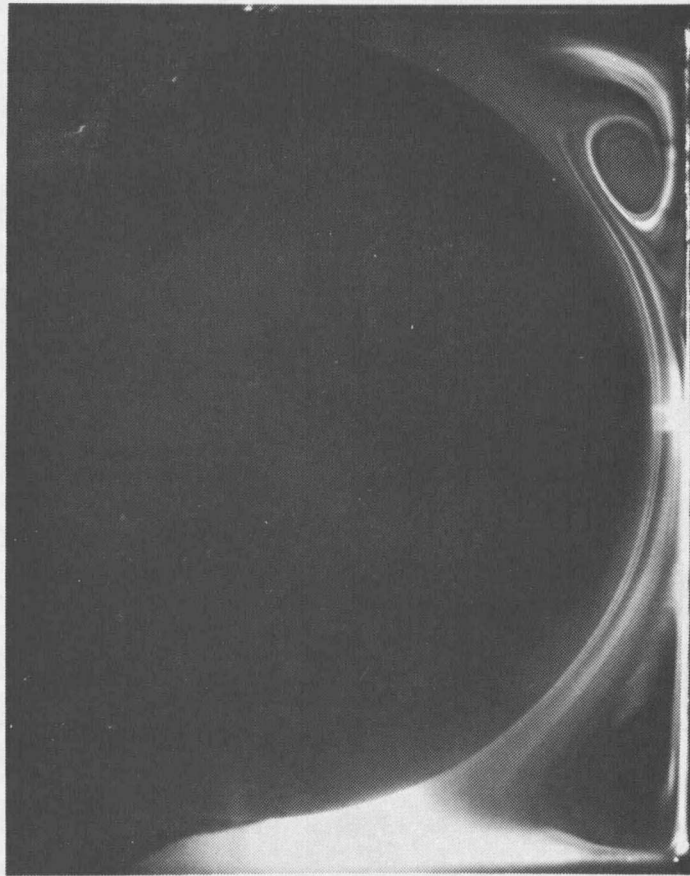


Figure 4.14 Flow Pattern in the Perpendicular Vertical Plane for

ID = 9.0 inches

$\Delta T = 14^{\circ}\text{F}$

$N_{\text{Gr}} = 1,070$

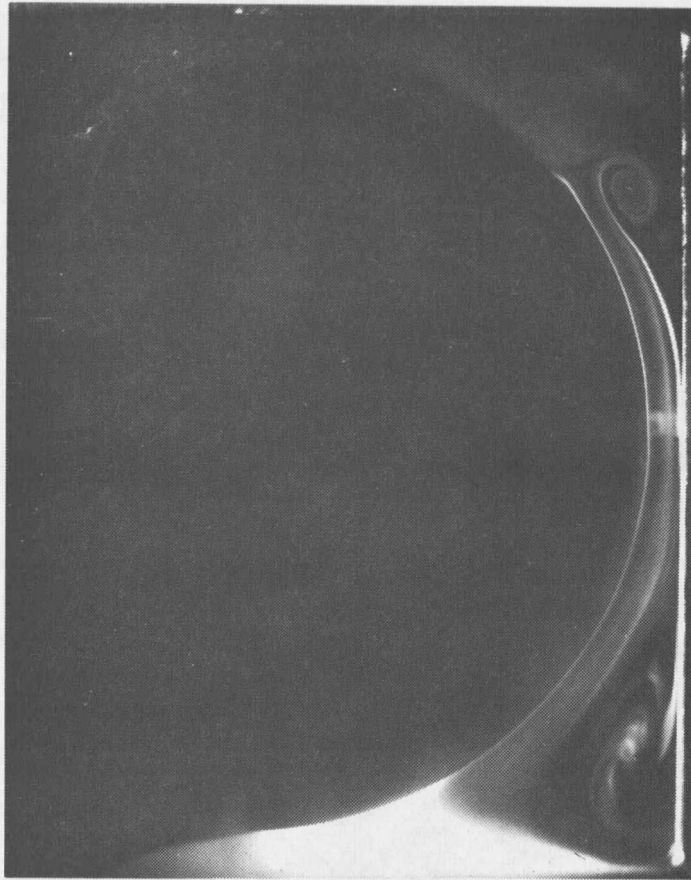


Figure 4.15 Flow Pattern in the Perpendicular Vertical Plane for

ID = 9.0 inches

$\Delta T = 14^{\circ}\text{F}$

$N_{Gr} = 1,070$

side by the high speed flow which followed the contour of the inner body. The fluid comprising the high speed flow originated from the lower axial region where the fluid was relatively stagnant. This high speed flow continued upward around the inner sphere, through the midplane and into the upper region.

In the upper region, the high speed boundary separated from the inner body at a point which formed a 45° angle with the upward vertical central axis. The boundary fluid separating from the inner body, combined with a three-dimensional flow near the top of the outer body to form an unsteady spiral formation. The flow in the vicinity of the upper axial region was indiscernable, but is postulated to be similar to the three-dimensional spiral flow reported by Yin (4) and Baughman (5) in a similar narrow region near the upper vertical axis formed by the concentric spheres they investigated. It is expected that forthcoming temperature profiles to be obtained in the heat-transfer apparatus will shed further light on this situation.

Figure 4.14 shows the spiral formed in the upper region by the high speed boundary fluid and fluid from the upper axial region. This spiral formation would then decrease in size, as shown in comparison of Figures 4.14 and 4.15, until

the whole flow pattern in the upper region was indiscernable. The spiral would then start small again, increasing in size until the cycle was completed. The whole cycle would then repeat itself at nonperiodic intervals.

It should be noted that at no time in the unsteady cycle did any noticeable amount of fluid flow downward along the outer body's side into the lower region. In order for continuity to be satisfied, fluid must enter the lower region from the upper region in a vertical plane other than the perpendicular vertical plane. This was observed to be the case in the diagonal plane where only one major flow region was noted that comprised the whole of the diagonal gap region.

The flow in the diagonal vertical plane consisted of high speed fluid flowing upward in the near vicinity of the inner body. This upward flow separated from the inner body about 15° down from the upward vertical central axis. The flow then followed the contour of the cube, along the top and down the side. No separation occurred in the downward flow. The main flow in the gap was an upward and inward radial flow that was noted to be unsteady at all the temperature differences investigated. The separation of the flow from the inner body was not temperature-difference dependent, but the degree of unsteadiness increased as the

temperature difference was increased.

Figure 4.16 shows a horizontal plane section for $\Delta T = 14^{\circ}\text{F}$. Evident in the photograph is the three-dimensional flow that was noted to be unsteady in the diagonal vertical plane.

SUMMARY OF RESULTS

In the first section of this chapter, descriptive analyses of the flow patterns were presented for each of the five spherical inner bodies investigated. Characterizations of the flow observed in a perpendicular vertical plane and in a diagonal vertical plane were reported, while observations of horizontal plane sections yielded supporting information. This section presents a summary of the similarities and dissimilarities of the results.

For all the temperature differences investigated with the 3.5 inch spherical inner body, $\Delta T = 24^{\circ}\text{F}$ to $\Delta T = 115^{\circ}\text{F}$, and the 4.5 inch spherical inner body, $\Delta T = 15^{\circ}\text{F}$ to $\Delta T = 91^{\circ}\text{F}$, the flow patterns in the perpendicular vertical plane were very similar. The flow pattern in the perpendicular plane was characterized by three distinct regions; (1) a relatively high velocity flow which basically followed the geometric boundary of the gap, (2) an upper central region that was characterized by at least one interior corner eddy.



Figure 4.16 Flow Pattern in a Horizontal Plane Section at the Midplane for

ID = 9.0 inches

$\Delta T = 14^{\circ}\text{F}$

$N_{\text{Gr}} = 950$

and minor three-dimensional flow, and (3) a lower region that was mostly slow flow with three-dimensional mixing motion. A vertical plume located around the upper vertical axis was always present indicating axisymmetry. The high speed downward flow along the outer body's edge separated from the edge below the midplane. The point of separation was temperature-difference dependent. It moved up the wall to a point very near the midplane at the highest temperature differences considered.

For all of the temperature differences investigated, the flow patterns in the diagonal vertical plane were similar. The diagonal vertical plane was characterized by three basic flow regions; (1) a high speed flow that followed the geometric configuration of the gap, (2) a large eddy formation in the upper central region, and (3) a hump-shaped drift region between the outer edge and the inner body. A slowly moving region near the downward vertical axis was apparent at lower temperature differences. A vertical plume which formed around the upper vertical axis indicated axisymmetry. Observations in the horizontal plane sections verified some of the three-dimensional flows and showed that the flow was symmetric with respect to both the diagonal vertical plane and the perpendicular vertical plane.

Similarities which existed in the perpendicular vertical plane and the diagonal vertical plane included:

(1) the high speed boundary flow and (2) an eddy formation in the upper central region. Dissimilarities included:

(1) a fluid separation of the downward flow from the wall in the perpendicular vertical plane and no separation in the diagonal vertical plane, (2) the shape of the eddy formation in the upper central region, and (3) the occurrence of the hump-shaped flow between the outer body and the inner body in the diagonal plane.

The foregoing summary of the 3.5 inch and 4.5 inch inner body results is applicable to the 5.5 inch spherical inner body for temperature differences investigated from $\Delta T = 28^{\circ}\text{F}$ to $\Delta T = 61^{\circ}\text{F}$ for the perpendicular vertical plane and to $\Delta T = 78^{\circ}\text{F}$ for the diagonal plane. Between $\Delta T = 61^{\circ}\text{F}$ and the upper limit investigated, $\Delta T = 97^{\circ}\text{F}$, an unsteady periodic spiral motion was noted in the upper central region of the perpendicular vertical plane. The period of the unsteadiness ranged from 6 seconds at $\Delta T = 61^{\circ}\text{F}$ down to 3 seconds at $\Delta T = 97^{\circ}\text{F}$. The high speed boundary flow and the separation point of the downward flow was unaffected by the periodic pulsation of the spiral eddy. In the lower region near the outer corner, a temperature-difference dependent spiral motion was noted for all the temperature differences

investigated.

Between $\Delta T = 78^{\circ}\text{F}$ and the upper temperature difference investigated, $\Delta T = 97^{\circ}\text{F}$, in the diagonal vertical plane an unsteady nonperiodic pulsation of the eddy in the upper central region was noted. The hump-shaped radial drift flow toward the inner body was also noted to be nonperiodically unsteady.

For all the temperature differences investigated with the 7.0 inch spherical inner body, $\Delta T = 13^{\circ}\text{F}$ to $\Delta T = 39^{\circ}\text{F}$, a nonperiodic unsteady flow was noted. The flow was characterized, in both the perpendicular vertical plane and the diagonal vertical plane, by the high speed fluid flowing upward around the inner sphere and then separating from the inner body. This separated flow divided between the upper central region and the region near the upper vertical axis. Nonperiodically, a rotating slug of fluid would leave the upper central axial region and "fall" into the upper central region, disturbing the flow in the upper central region momentarily. After this disturbance died out, the whole process repeated itself nonperiodically. The similarity of the flow in the diagonal vertical plane and the perpendicular vertical plane contrasts with the different patterns observed in the perpendicular vertical plane and the diagonal vertical plane for the smaller inner bodies.

The patterns that were observed for the 9.0 inch diameter inner spherical body for all the temperature differences investigated, $\Delta T = 13^{\circ}\text{F}$ to $\Delta T = 32^{\circ}\text{F}$, were non-periodically unsteady. The flow in the perpendicular vertical plane was divided into two regions by the close proximity of the inner and outer bodies at the midplane. In the upper region, the flow was characterized by a separation from the inner body and "falling" slugs of fluid, similar to that reported for the 7.0 inch inner body. The lower region was characterized by a large spiral eddy formation. In the diagonal plane, a separation from the inner body also occurred and the whole flow pattern, including the radial drift flow, was unsteady and three-dimensional. The flow for all the temperature differences investigated with the 7.0 inch inner body and the 9.0 inch inner body was noted to be nonsymmetric with respect to both the perpendicular and diagonal vertical planes.

CHAPTER V

CONCLUSION

Descriptive analyses of the flow characterizations are presented in this thesis. The flow was investigated in (1) a vertical plane perpendicular to the cubical outer body's side and passing through the inner body's vertical axis, (2) a vertical plane passing through a vertical edge of the cubical outer body and the inner body's vertical axis, and (3) in horizontal plane sections, one at the midplane and one two inches above the midplane. In most cases, these planes of observation were adequate to describe the natural convective fluid flow in the gap. Observations in other planes might be useful in further analysing the flow, especially when a major three-dimensional flow exists. However, an unwieldy number of planes of observation would be required to completely relate the extent of the three-dimensional flows, especially when they are unsteady.

Future work with the apparatus is planned. Other test fluids are to be used to extend the Prandtl number range. This author feels that in the event three-dimensional flows are noted, and it is desired to determine the extent of the three-dimensional effects, additional planar observations should be conducted.

One improvement to the apparatus used to visually investigate the flow should be made. The light intensity in

certain regions of the field tends to be inadequate to visualize the flow. Either the intensity of the light source should be increased, or a reflection system should be made in order that certain dim regions of the flow may be better visualized. This would aid in better describing the flow in certain regions such as the upper central region or the upper axial region.

With the results of this investigation being the first reported concerning the phenomena of natural convection between an inner body and a cubical enclosure, no direct comparison with previous results can be made. However, the qualitative analysis herein presented should be an aid in analysing the heat transfer phenomena between the inner body and its cubical enclosure. The heat transfer experiments are presently being conducted at Montana State University.

APPENDIX

COMPUTER PROGRAM

```

C.....NATCON PROJECT
C.....L. LOREN EYLER
C
C.....A PROGRAM TO REDUCE DATA TO THE DESIRED FORM FOR AIR AS THE GAP
C      WORKING FLUID
C.....INPUT REQUIRED
C
C.....CARD 1) NO. OF DATA SETS
C          2) CUBE LENGTH, SPHERE DIAMETER, AMB. PRESSURE==(3F9.4)
C          3) RUN NO., NO. INNER TC'S, NO. INNER + NO. OUTER TC'S==(3I3)
C          4) EMF READINGS (MV) OF INNER TC'S==(8F5.3)
C          5) EMF READINGS (MV) OF OUTER TC'S==(11F5.3)
C.....CARDS 3) TO 5) COMPRISE A DATA SET
      REAL ID,IT ,ITAVG,IR      ,MAXDEVIT,MAXDEVCT
      DIMENSION OT(30),IT(30),E(30),DEV(30),C(8)
      DOUBLE PRECISION TOT
      READ(105,19)I
19  FORMAT(I5)
      READ(105,11) OD,ID,BARO
11  FORMAT(3F9.4)
      DO 500 NNN=1,I
      READ(105,21) RUN,MM,MMM
21  FORMAT(3I3)
      WRITE(108,50) RUN
50  FORMAT('1','RUN NO. = ',I3)
100 WRITE(108,52)
52  FORMAT('1','/ ','FLUID ..... AIR')
      DIAR = OD-ID
      GAP = (OD-ID)/2.
      WRITE(108,54) OD,ID,DIAR,GAP
54  FORMAT('0','CUBE LENGTH = ',F10.4,' INCHES',//,'INNER DIA.   = ',
$F10.4,' INCHES',//,'RATIO           = ',F10.4,'/ ','GAP           = ',
$F10.4,' INCHES',// )
      READ(105,12) (E(J), J=1,MM)
12  FORMAT(8F5.3)
      READ(105,13) (E(J),J=MM+1,MMM)

```

```

13 FORMAT(11F5.3)
C.... CONVERSION OF MILLIVOLTS TO DEGREES RANKINE
C(1)=491.96562
C(2)=46.381884
C(3)=-1.3918864
C(4)=0.15260798
C(5)=-0.020201612
C(6)=0.0016456956
C(7)=-6.6287090/(10.**5)
C(8)=1.0241343/(10.**6)
DO 200 N=1,MMM
TOT=0.00
DO 1 JJJ=1,8
1 TOT=TOT+C(JJJ)*(E(N)**(JJJ-1))
T=TOT
IF(N.GE.MM+1) GO TO 302
IT(N)=T
GO TO 201
302 CONTINUE
OT(N)=T
201 CONTINUE
200 CONTINUE
SUM = 0.
DO 103 II=1,MM
SUM = SUM+IT(II)
103 CONTINUE
ITAVG = SUM/MM
SUM = 0.
DO 104 KK=MM+1,MMM
SUM = SUM+OT(KK)
104 CONTINUE
OTAVG=SUM/(MMM-MM)
DT = ITAVG-OTAVG
WRITE(108,59)
59 FORMAT( ' OUTER CUBE TEMP      ',10X,'DEVIATION',15X,'% DEVIATION',
S/ )

```

```

MAXDEVOT = 0.
DO 105 J=MM+1,MMM
DEV(J) = OTAVG-OT(J)
DUM2=ABS(DEV(J))
IF(DUM2.GT.MAXDEVOT) MAXDEVOT=DUM2
ERROR = DEV(J)/OTAVG*100.
WRITE(108,55) OT(J), DEV(J), ERROR
55 FORMAT(' ',4X,F10.4,11X,F10.4,16X,F10.4)
105 CONTINUE
WRITE(108,60)
60 FORMAT(' ', 'INNER BODY TEMP.', '/' )
MAXDEVIT=0.
DO 106 J=1,MM
DEV(J) = ITAVG-IT(J)
DUM2=ABS(DEV(J))
IF(DUM2.GT.MAXDEVIT) MAXDEVIT=DUM2
ERROR = DEV(J)/ITAVG*100.
WRITE(108,55) IT(J),DEV(J), ERROR
106 CONTINUE
PERDEVIT=MAXDEVIT/DT*100.
PERDEVOT=MAXDEVOT/DT*100.
WRITE(108,56) ITAVG,MAXDEVIT,OTAVG,MAXDEVOT,DT,PERDEVIT,PERDEVOT
56 FORMAT('1',/, 'MEAN INNER BODY TEMP.      = ',F10.4,' R',/, 'MAX. I
INNER BODY DEV.      = ',F10.4,' R',/, 'MEAN OUTER CUBE TEMP.
1 = ',F10.4,' R',/, 'MAX. OUTER CUBE DEV.      = ',F10.4,' R',/,
1MEAN TEMP. DROP ACROSS GAP = ',F10.4,' R',/, 'INNER BODY DEVIATION
1 (MAX) = ',F10.4,' % MEAN TEMP. DROP',/, 'OUTER CUBE DEVIATION (MA
1X) = ',F10.4,' % MEAN TEMP. DROP',/,)
IR = ID/2.
RAVG = (OR+IR)/2.
G = 32.174
K = 0
TM = (ITAVG+OTAVG)/2.
WRITE(108,61) TM
61 FORMAT('0',20X, 'PROPERTIES BASED ON THE ARITHMETIC MEAN TEMPERATUR
$E',/,/,/, 'ARITHMETIC MEAN TEMP. = ',F10.4,' R')

```

```

C.... SPECIFIC HEAT OF AIR
SH=C.22797749+2.236775/(10.**5)*TM
C.... VISCOSITY OF AIR
VIS=TM**1.8432299/(EXP(6.0133834)*(TM+134.375)**1.334705)
C.... THERMAL CONDUCTIVITY OF AIR
XP = 0.1
10 X = XP
F=(-8.5964965)+34490.89*X+868.23837*X*X+8056583.8*X* X*X= TM
FP=34490.89+2.*868.23837*X+3.*X*X*8056583.8
XP = X-F/FP
IF(ABS((XP-X)/X)=0.0001)20,20,10
20 CON = XP
COND = CON
C.... DENSITY OF AIR AT LOCAL ATMOSPHERIC PRESSURE
P = BARO*.491
RHO = BARO*.491*144./(53.34*TM)
DEN = RHO
WRITE(108,101) P
101 FORMAT(' ',//,'ATMOSPHERIC PRESSURE = ',F10.4,' PSI')
C.... EXPANSION COEF. OF AIR
BETA = 1.0/TM
B = BETA
C.... GRASHOF NUMBER BASED ON THE GAP THICKNESS
GR=C*B*DEN**2.*GAP**3.*DT*3600.0**2./(1728.0*VIS**2.)
PR = VIS*SH/COND
RA = PR*GR
WRITE(103,57) VIS, SH, COND, DEN, B
57 FORMAT(' ',//,'VISCOSITY = ',F10.4,' LBM/FT HR',//,'S
SPECIFIC HEAT = ',F10.4,' BTU/LBM R',//,'THERMAL CONDUCTIV
ITY = ',F10.4,' BTU/HR FT R',//,'DENSITY = ',F10.
4,' LBM/CU FT',//,'EXPANSION COEF. = ',F10.4,' 1/R')
WRITE(108,58) PR, GR, RA
58 FORMAT(' ',//,'PRANDTL NO. = ',F15.4,//,'GRASHOF NO.
= ',F15.4,//,'RAYLEIGH NO. = ',F15.4,//,'1')
WRITE(108,600)
600 FORMAT(////////,15X,'*',27X,'*',22X,'*',27X,'*',/,13X,'*',31X,'*',18

```

\$X,'*',31X,'*',/,11X,'*',35X,'*',14X,'*',35X,'*',/////////
\$////////,11X,'*',35X,'*',14X,'*',35X,'*',/,13X,'*',31X,'*',18X,'*',3
\$1X,'*',/,15X,'*',27X,'*',22X,'*',27X,'*')

500 CONTINUE

END

END

BIBLIOGRAPHY

1. Bishop, E. H., "Heat Transfer by Natural Convection between Isothermal Concentric Spheres", Ph.D. Dissertation, University of Texas, 1964.
2. Weber, N., "Natural Convection Heat Transfer between a Body and Its Spherical Enclosure", Ph.D. Dissertation, Montana State University, 1971.
3. McCoy, C. T., "Natural Convection from a Body to Its Spherical Enclosure", M.S. Thesis, Montana State University, 1972.
4. Yin, S., "Natural Convective Flow between Isothermal Concentric Spheres", Ph.D. Dissertation, Montana State University, 1972.
5. Baughman, R. C., "Natural Convective Flow between a Body and Its Spherical Enclosure", M.S. Thesis, Montana State University, 1973.
6. Holman, J. P., Heat Transfer, second edition, McGraw-Hill Book Company, New York, 1968, Chapter 7.
7. Jakob, M., Heat Transfer, Volume I, John Wiley and Sons, Inc, New York, 1949, Chapters 21-23.
8. Newell, M. E., and Schmidt, F. W., "Heat Transfer Laminar Convection Within Rectangular Enclosures", Transactions of the ASME Journal of Heat Transfer, Volume 88, 1969, pp. 1-9.
9. Batchelor, G. K., "Heat Transfer by Free Convection across a Closed Cavity between Vertical Boundaries at Different Temperatures", Quarterly of Applied Mathematics, Volume XII, 1954, pp. 209-233.
10. Davis, G., "Laminar Free Convection in an Enclosed Rectangular Cavity", International Journal of Heat and Mass Transfer, Volume 11, 1968, pp. 1675-1693.

11. Wilkes, J. O., and Churchill, S. W., "The Finite-Difference Computation of Natural Convection in a Rectangular Enclosure", American Institute of Chemical Engineers Journal, Volume 12, 1966, pp. 161-166.
12. Powe, R. E., Carley, C. T., and Carruth, S., "A Numerical Solution for Natural Convection in Cylindrical Annuli", Transactions of ASME Journal of Heat Transfer, Volume 89, 1971, pp. 210-220.
13. Bishop, E. H., Koflat, R. S., Mack, L. R., and Scanlan, J. A., "Convection between Concentric Spheres", Proceedings of the 1964 Heat Transfer and Fluid Mechanics Institute, W. Gredt and S. Levy, editors, Stanford University Press, 1964, pp. 69-80.
14. Bishop, E. H., Koflat, R. S., Mack, L. R., and Scanlan, J. A., "Photographic Studies of Convection Patterns between Concentric Spheres", Society of Photo-Optical Instrumentation Engineers Journal, Volume 3, 1964-65, pp. 47-49.
15. Bishop, E. H., Mack, L. R., and Scanlan, J. A., "Heat Transfer by Natural Convection between Concentric Spheres", International Journal of Heat and Mass Transfer, Volume 9, 1966, pp. 649-662.
16. Scanlan, J. A., Bishop, E. H., and Powe, R. E., "Natural Convection Heat Transfer between Concentric Spheres", International Journal of Heat and Mass Transfer, Volume 13, 1970, pp. 1857-1872.
17. Yin, S., Powe, R. E., Scanlan, J. A., Bishop, E. H., "Natural Convection Flow Patterns in Spherical Annuli", International Journal of Heat and Mass Transfer, in press, 1973.



3 1762 10013637 1

THESES

N378

Ey47

cop.2

Eyler, Lucius L

Natural convective
flow patterns between an
isothermal heated
inner body and ...

NAME AND ADDRESS

PFE

DR. LUCIUS L. EYLER
1011 S. TERRY ST.
BOZEMAN, MONT. 59717

(R) JT

THESES

R

R

R

R

N378

Ey47

cop.2

R 1