Natural convective flow between an isothermal spherical body and its isothermal cubical enclosure
by Thomas Keith Larson

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Mechanical Engineering
Montana State University

Abstract:
Qualitative descriptions of the natural convective flow patterns between isothermal heated spherical bodies and an isothermal cooled cubical enclosure are presented. Inner bodies used had diameters of 4.5, 7.0, and 9.0 inches', and the cubical enclosure measured 9.9 inches on a side. Test fluids used in the gap between the spheres and the cube included water, 20 cs silicone oil, and 350 cs silicone oil. The silicone oils are Dow Corning 200 fluids with 20 and 350 representing the kinematic viscosity in centistokes at 25°C. All investigations were conducted with the inner body concentrically located within the enclosure. Motion pictures and still photographs of the flow patterns observed were taken to aid in the descriptions of the patterns.

For most of the fluids and geometries tested, the flow for small temperature differences was found to maintain a peripheral pattern in which high-speed fluid layers followed the solid boundaries of the system. Larger temperature differences usually resulted in separation of the high-speed layer moving over the surface of the inner body and unsteady vortex structures in the upper portion of the gap. Unsteadiness occurring with the silicone oils as test fluids was usually confined to small regions of the gap since these oils were quite viscous and acted as unsteady flow dampers. Unsteadiness occurring with water as the test fluid was generally noted to affect the whole upper central region of the gap. Some three-dimensional activity was noted for nearly all cases investigated. This is to be expected because of the lack of symmetry resulting from having a spherical body located within a cubical enclosure. Summaries of the experimental results obtained are given in Tables 4.1-4.3 and should help to categorize the flows observed.

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Signature Thomas K. Larson

Date August 6, 1974

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by

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A thesis submitted in partial fulfillment
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ABSTRACT

Qualitative descriptions of the natural convective flow patterns between isothermal heated spherical bodies and an isothermal cooled cubical enclosure are presented. Inner bodies used had diameters of 4.5, 7.0, and 9.0 inches, and the cubical enclosure measured 9.9 inches on a side. Test fluids used in the gap between the spheres and the cube included water, 20 cs silicone oil, and 350 cs silicone oil. The silicone oils are Dow Corning 200 fluids with 20 and 350 representing the kinematic viscosity in centistokes at 25°C. All investigations were conducted with the inner body concentrically located within the enclosure. Motion pictures and still photographs of the flow patterns observed were taken to aid in the descriptions of the patterns.

For most of the fluids and geometries tested, the flow for small temperature differences was found to maintain a peripheral pattern in which high-speed fluid layers followed the solid boundaries of the system. Larger temperature differences usually resulted in separation of the high-speed layer moving over the surface of the inner body and unsteady vortex structures in the upper portion of the gap. Unsteadiness occurring with the silicone oils as test fluids was usually confined to small regions of the gap since these oils were quite viscous and acted as unsteady flow dampers. Unsteadiness occurring with water as the test fluid was generally noted to affect the whole upper central region of the gap. Some three-dimensional activity was noted for nearly all cases investigated. This is to be expected because of the lack of symmetry resulting from having a spherical body located within a cubical enclosure. Summaries of the experimental results obtained are given in Tables 4.1-4.3 and should help to categorize the flows observed.

NOMENCLATURE

Symbol	Description
a, b	Characteristic dimensions of system
C_p	Specific heat
D	Characteristic dimension
Dev	Percent deviation (equation 4.2)
g	Acceleration of gravity
k	Thermal conductivity
L	Length ratio
N_{Gr}	Grashof number (equation 2.1)
N_{Pr}	Prandtl number (equation 2.2)
N_{Ra}	Rayleigh number (equation 2.4)
r_i	Inner body radius
r_o	Distance from center of inner body to enclosure
T_{am}	Arithmetic mean temperature (equation 4.1)
$T_{i,av}$	Average inner body temperature
$T_{o,av}$	Average outer body temperature
T_o	Local outer body temperature
β	Coefficient of thermal expansion
ΔT	Temperature difference $(T_{i,av} - T_{o,av})$
Θ	Angular position measured from upper vertical axis of inner body

Symbol	Description
ρ	Density
μ	Absolute viscosity

CHAPTER I

INTRODUCTION

Until the last decade, the bulk of the literature related to natural convection concerned the convective process from a body to an infinite surrounding medium. Increased interest in the area of natural convection heat transfer from a body to a finite enclosure has been generated by the need for more accurate heat transfer rate predictions from a body to its enclosure. Projected applications may concern nuclear reactor core design, room heating, instrument packaging, and fire fighting techniques.

The need for experimental work in the area of natural convection in finite enclosures arises from the inherent complexity of the governing equations. The defining partial differential equations are nonlinear and coupled; thus no general solution is available. Additional difficulties complicating the situation are (1) the usual simplifing assumptions concerning boundary layers are not valid, (2) boundary conditions become unknown as flow unsteadiness develops, and (3) pressure distributions in the finite enclosure are unknown.

Experimental work done by Bishop (1)*, McCoy (2), Weber (3), and Scanlan et al (4) has shown that heat transfer data can be correlated to yield empirical relations predicting the convective heat transfer rate from a body to a spherical enclosure. Since natural convection is

* Underlined numbers in parentheses refer to references in the bibliography

a combination of fluid flow and thermal phenomena, it is desirable to visualize the flow patterns existing in the finite enclosure. Knowledge of the flow patterns in conjunction with the heat transfer data and temperature profiles provides a deeper understanding of the convective process.

The objective of this experimental investigation was to photograph and qualitatively describe the fluid flow patterns resulting from the convective interaction between an isothermal spherical body and its isothermal cubical enclosure. All investigations were conducted with the spherical body located concentrically within the cubical enclosure. Test fluids used in the gap between the sphere and its enclosure included water and two different silicone oils. Similar work has been reported by Baughman (5) and Yin (6). Their experiments were conducted with a spherical rather than a cubical enclosure. Directly related work, reported by Eyler (7), was done utilizing air as the medium between the sphere and the cubical enclosure.

This work is part of a continuing project at Montana State University. The results obtained add to the currently available information and hopefully will supplement the heat transfer experiments now in progress.

CHAPTER II

LITERATURE REVIEW

Natural convection is a term used to describe transport processes in fluids wherein the motion is driven by the interaction of a difference in density with an acceleration field (such as gravity or rotation). Natural convection heat transfer is then a form of energy exchange caused by the motion of a fluid. Motion of the fluid is created by a bouyancy force resulting from the interaction between the density differences within the fluid and the acceleration field.

Review of the literature reveals that some analytical solutions are available for natural convection from a body to an infinite surroundings and that some solutions exist for a few simple enclosures. Examples can be found in Gebhart (8), Jakob (9), Holman (10), Eckert and Carlson (11), and Batchelor (12). For more complex geometries, however, experimental methods must be relied upon because of the complexity of the governing equations. For this reason, a number of experimental studies concerning natural convective flow in an enclosure have been reported.

Jakob (9) derived some basic relations on heat transfer in natural convection using the principle of similarity. He used both the differential and the dimensional methods to determine the important non-dimensional parameters. The resulting dimensionless groups are

$$N_{Gr} = \frac{g\beta\rho^2 D^3 \Delta T}{\mu^2} \qquad (2.1)$$

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

and

$$L = \frac{a}{b} . \qquad (2.3)$$

In the above equations, N_{Gr} is termed the Grashof number and N_{Pr} is the Prandtl number. The parameter L is the ratio of a and b, the characteristic dimensions of the system under investigation. Another nondimensionalgroup, the Rayleigh number (N_{Ra}), is also useful. The Rayleigh number is defined as the product of the Grashof number and the Prandtl number, or

$$N_{Ra} = N_{Gr} \cdot N_{Pr} . \qquad (2.4)$$

Initial investigations of the natural convective phenomena in a spherical annulus were carried out by Bishop (1). All of his investigations were done using air as the working fluid and with the inner sphere concentrically located within the outer sphere. Heat transfer results, temperature profiles, and qualitative information about the fluid-flow behavior are reported. Visualization studies were conducted for diameter ratios of 1.19, 1.37, 1.72, 2.53, and 3.14 and for temperature differences from 5°F to 60°F. Bishop reported the occurrence of three basic flow patterns, (1) the "cresent-eddy" type, (2) the "kidney-shaped-eddy" type, and (3) the "falling-vortices" type.

The most common flow pattern, the "crescent-eddy", was noted to occur at all temperature-differences studied for diameter ratios of 1.37

and 1.72. For diameter ratios of 1.19, 2.53, and 3.14 the "cresent-eddy" pattern occurred only at small temperature differences. The "kidney-shaped-eddy" pattern, a modification of the crescent-eddy type, was noted to occur for diameter ratios of 2.53 and 3.14 at moderate to large temperature differences. Both the "crescent-eddy" and "kidney-eddy" type patterns were noted to be steady with time. Three basic regions were apparent in both patterns. These were (1) a thin layer of high-speed fluid in the close vicinity of each sphere, (2) a central region containing slowly moving fluid, and (3) a region of transition between each high speed layer and the central region.

The only unsteady pattern observed by Bishop, the "falling-vortices" type, occurred at moderate to high temperature differences for a dimater ratio of 1.19. This unsteady pattern was characterized by the formation of counter-rotating pairs of vortices in the region near the upper vertical axis of the inner sphere. The vortices would then coalesce and merge into the outer sphere boundary flow, momentarily disrupting the central region.

Further natural convective studies utilizing a spherical annulus were conducted by Yin (6). Diameter ratios of 1.40, 1.78, and 2.17 were used with air as the working fluid. Studies with water as the working fluid were conducted with diameter ratios of 1.09, 1.40, 1.78, and 2.17. Investigations with air extended the data of Bishop (1) to a larger temperature difference. Differences observed by Yin at larger temperature differences were (1) violent interior contractions, (2) slight sideways oscillations of the chimney, and (3) a three-dimensional spiral motion in the upper portion of the annulus for the smallest diameter ratio. With water as the working fluid, four flow patterns, two steady and two unsteady, were observed. These patterns were (1) the steady "dog-face" type, (2) the unsteady "dog-face" type, (3) the steady "interior tertiary" type, and (4) the unsteady three-dimensional spiral flow. The most common pattern was the steady "dog-face" flow. It occurred at small temperature differences for all diameter ratios investigated except the smallest. The pattern was characterized by three distinct regions, namely (1) regions of high-speed flow adjacent to each sphere, (2) a low speed interior region, and (3) a central stagnant region. The "interior tertiary" flow pattern occurred at large temperature differences for a diameter ratio of 1.78. This pattern was noted to be steady. The "unsteady dog-face" pattern was observed at large temperature differences for a diameter ratio of 2.17. Characteristic of the pattern was the formation and shedding of cells in the interior region. The three-dimensional spiral was an unsteady pattern that occurred at large temperature differences for diameter ratios of 1.09 and 1.40. For this case the upper portion of the annulus was dominated by a three-dimensional spiral flow.

Baughman (5) investigated the case of eccentric spheres with air and a silicone oil as the test fluids. He also used water and the silicone oil as test fluids in concentric hemispherically ended cylinder studies. Results obtained with the eccentric spheres and air as the gap medium were similar to the concentric sphere results discussed above. Some new type flow characteristics were observed with the silicone oil as the test medium in the eccentric sphere studies. A diameter ratio of 2.17 was noted to generally yield a basic crescent shape. Negative eccentricities (inner body below the center of the outer body) tended to display a "climbing vortices" type pattern. Characteristic of this pattern was the formation of cells, one on each side of the thermal plume, and their subsequent rotation upward along the plume. Falling vortices and three-dimensional vortices were postulated to have occurred for positive eccentricities with a diameter ratio of 1.40. Negative eccentricities for this diameter ratio yielded (1) vortex drifting, (2) formation of multiple cells, and (3) undulating tendencies of the high-speed fluid layer on the surface of the inner body. Flow patterns resulting with the cylinders as the inner body and the silicone oil as the gap medium were similar to the eccentric sphere studies. Cylinder studies with water as the test fluid yielded patterns similar to the concentric sphere results obtained by Yin (6). A detailed review of the particular patterns can be found in Baughman (5).

Fluid flow patterns between a hemispherically ended cylinder and a spherical enclosure have also been investigated by Teng (13). His studies were conducted with the cylinder concentrically located within the enclosure. Air and a silicone oil of different absolute viscosity than that used by Baughman were used as test fluids.

Additional work, primarily concerning heat transfer data and temperature profiles, has been done utilizing a spherical enclosure and various inner bodies and several different test fluids. Examples are Weber, Powe, Bishop, and Scanlan (14), McCoy, Powe, Bishop, Weber, and Scanlan (15), and Scanlan, Bishop, and Powe (4).

Natural convective flow patterns between an isothermal sphere concentrically located within a cubical enclosure have been investigated by Eyler (7). Spheres of 3.50, 4.50, 5.50, 7.00, and 9.00 inches diameter were investigated, and air was used as the gap medium. The 3.50 inch and 4.50 inch spheres yielded steady flows characterized by three distinct regions for all temperature differences investigated. These regions were (1) a high-speed boundary region, (2) an upper interior region characterized by at least one eddy formation, and (3) a slow moving lower region. For small temperature differences, the 5.50 inch sphere exhibited flow characteristics similar to the 3.50 inch and 4.50 inch bodies. At high temperature differences, unsteady flow developed and was characterized by a periodic pulsating eddy formation in the upper central region. Both the 7.00 inch and 9.00 inch bodies yielded nonperiodic unsteady flows at all temperature differences. For these two bodies, slugs of fluid were noted to randomly "fall" from the upper vertical axial region into the upper central region.

CHAPTER III

EXPERIMENTAL APPARATUS AND PROCEDURE

EXPERIMENTAL APPARATUS

An existing apparatus used by Eyler (7) in his investigations with air as the test fluid was partially redesigned to permit the use of test fluids other than air in the study of natural convective flows and to allow a water cooling system to be employed. Figures 3.1 and 3.2 show the experimental apparatus and a schematic representing the functions of the peripheral equipment. The cubical enclosure seen in the center of Figure 3.1 contains the isothermal cubical test space and its inner body. Both the test space and inner body will be described in detail later. Peripheral equipment shown in the photograph includes (1) the water cooling system on the left, (2) inner body temperature controlling instruments to left and below, (3) temperature monitoring instruments and light source on the right, and (4) the test fluid reservoir in the upper left corner.

The main purpose of the approximately 14.0 inch cubical enclosure shown in Figure 3.1 was to allow a closed cooling system to be employed. The enclosure functioned as a water jacket surrounding the inner cubical test space. The water jacket was equipped with individual channels so that cooling water could be circulated independently over the four sides, the top, and the bottom of the cubical test space. The water cooling system was constructed so that the coolant flow rate in each channel could be controlled by means of valves. The network of plumbing required

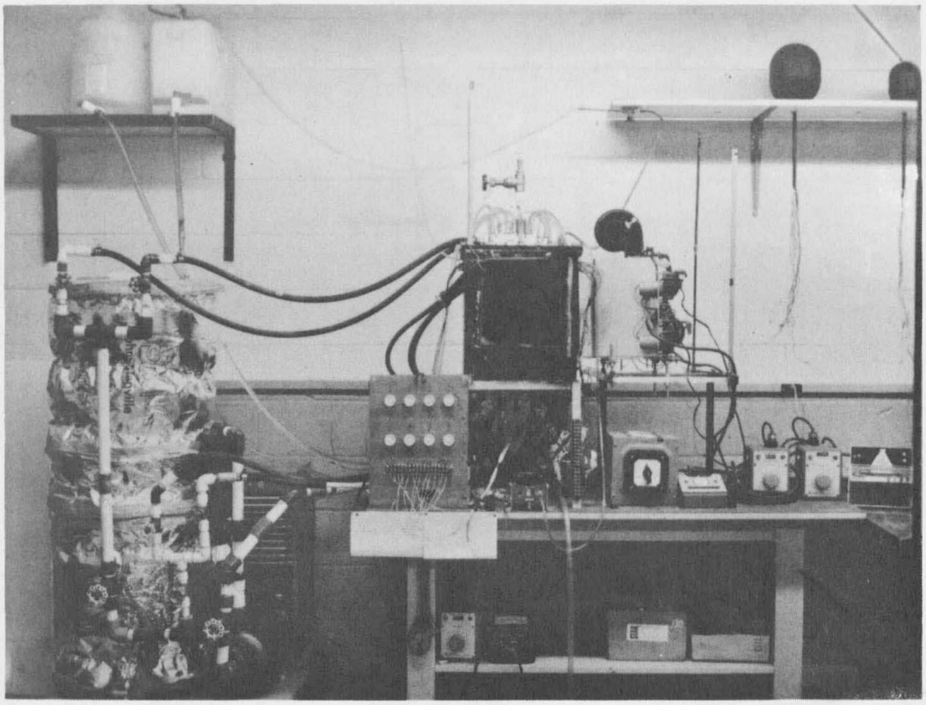

Figure 3.1 Apparatus Assembly