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COLD JETS OR HOT PLUMES? THE BIFURCATION STRUCTURE OF NATURAL CONVECTIVE FLOWS BETWEEN A COLD PLATE AND A HOT BODY

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ABSTRACT

In general, the topology of a natural convective flow pattern does not change with increasing Rayleigh number (Ra) and is independent of the initial temperature of the fluid. Normally the main effect of increasing Ra is that the convective velocities increase, the boundary layers become thinner and the overall heat transfer increases monotonically.

Here we present a numerical study of the flow behaviour for one geometry, originating as a room air conditioning application, that exhibits remarkable variation. There are two distinct flow patterns. The first has a plume rising from the heating body which drives the primary recirculations. This is the *normal* flow pattern for all such enclosure type geometries. The second has a jet of cold air dropping from the cold plate onto the heating body and driving the primary recirculations in the opposite directions to those of the first pattern.

There is an abrupt transition from one flow pattern to the other and back to the first, as the Rayleigh number increases. The critical Rayleigh numbers also depend on the initial temperature of the air. This produces a complex bifurcation structure for the flow in this type of geometry.

GEOMETRY

The geometry consists of an adiabatic 3 m square box. It is heated by a hot isothermal rectangular body attached to the middle of the bottom of the box. The cavity is filled with air and is cooled by a very thin plate (1 cm thick) parallel to and 3 cm from the ceiling. This geometry arises from a study of supplementary cooling of offices using large rectangular cooling panels. This is a computationally difficult geometry because of the large range of length scales that must be accurately resolved. Flow within a 1 cm channel (between the panel and the ceiling) in a 3 m cavity must be resolved, in addition to the normal difficulties of resolving very thin thermal boundary layers and small scale flow features that occur at high Ra. The bifurcation structure occurs for Ra of the order $10^5 - 10^8$ and would be significant for cavities 0.1 - 0.5 m and temperature difference of 5-50^{o}C.

NUMERICAL METHOD AND ACCURACY

The simulations used in this study were performed using the CSIRO finite element CFD package *Fastflo*. The algorithm involves the segregated solution of the Boussinesq equations for natural convection (see Rohsenow et. al. 1985 for details). The Navier-Stokes part of the equations are solved using a very robust, accurate and stable operator-splitting method. The simulations are time accurate and fully transient. This is required to detect the instabilities and correctly determine the relative strengths of the jets that determine which flow structure will dominate. The numerical scheme has been successfully tested for three different geometries and the Nu validated against good experimental results for one geometry (see Cleary 1995a&b for details).

These simulations were run using unstructured triangular meshes at three resolutions, consisting of 2,000, 3,000 and 4,000 corner nodes (corresponding to total node numbers of 7708, 11667 and 15585). Mesh refinement tests shows 2000 corner node meshes was adequate for Ra $< 10^6$. To ensure high accuracy the higher resolution 3000 corner mesh was used. For Ra between 10^6 and 10^7, the 3000 corner node mesh was adequate, but a 4000 corner mesh was used. Above this the 4000 corner node mesh was needed to guarantee accuracy. For Ra$>3\times10^7$ finer meshes are required.

THE TWO FLOWS: JETS AND PLUMES

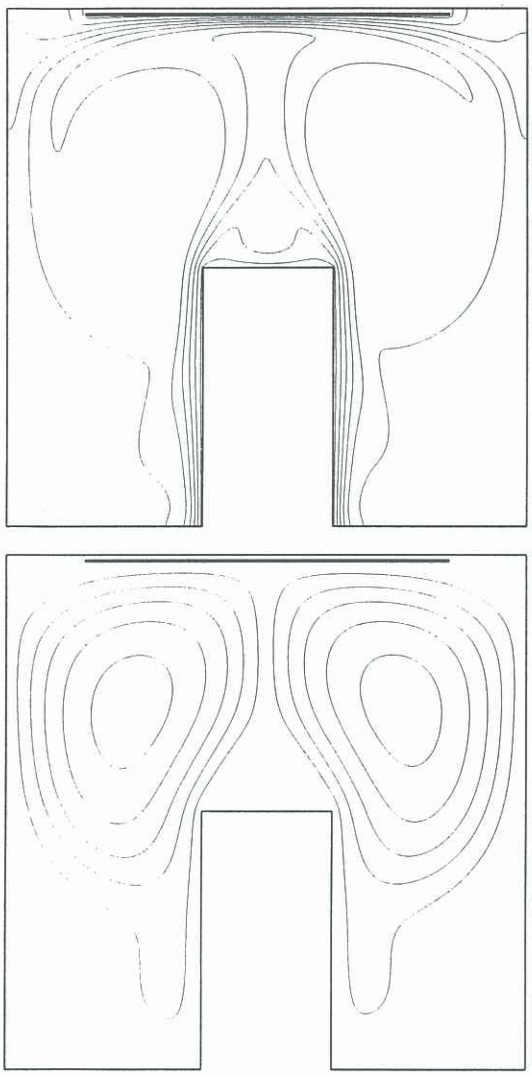

Figure 1: TYPE I FLOW (isotherms and streamlines)

The Type I flow (shown in Figure 1 for Ra $= 4\times10^6$ and $T_0 = 0.3$) is the normal flow pattern for this type of geometry and consists of a plume that rises from the heating body to the cold plate and generates two primary recirculations. The fluid on the right rotates clockwise and the fluid on the left anticlockwise. The plume is formed by the merging of the jets of hot air rising from the sides of the heating body. This Type I flow is asymptotically steady. The flow pattern is symmetric and the plume is stable. The isotherms are concentrated directly under the plate and near the vertical surfaces of heating body. Note the bulge in the middle of the later isotherms. This indicates higher heat transfer rates at the bottom and top of the sides of the heating body. The heat transfer near the top is strongly enhanced by the proximity of the recirculations. For other Ra and T_0 combinations this flow pattern can be asymptotically unsteady. The plume oscillates sideways, driven by the alternating oscillation of the hot jets. This probably relates to the boundary layers becoming unstable.

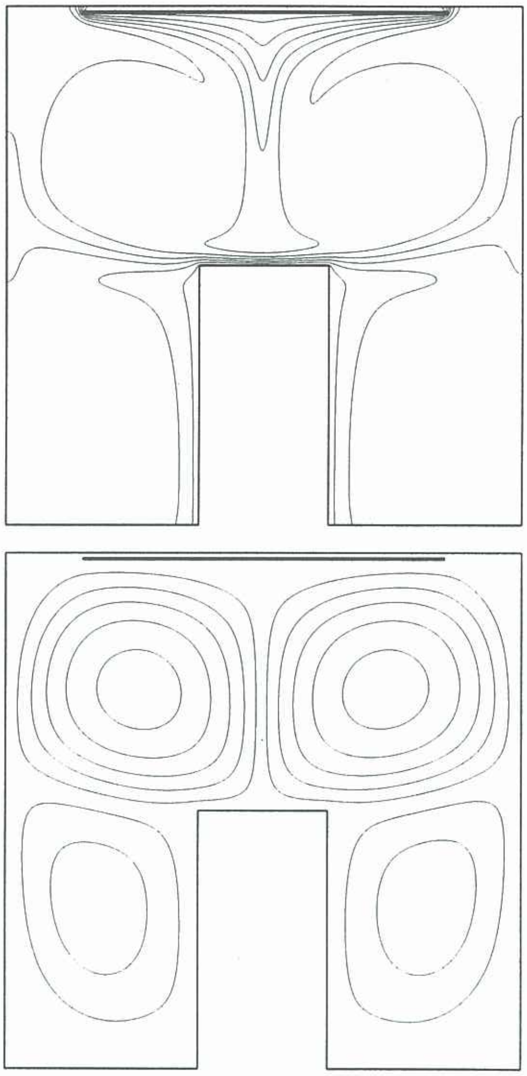

Figure 2: TYPE II FLOW (isotherms and streamlines)

The Type II flow (shown in Figure 1 for Ra $= 4\times10^6$ and $T_0 = 0.92$) consists of a cold jet that drops from the middle of the bottom of the cold plate to the top of the hot body. This separates the two primary eddies whose sense of recirculation is opposite of that in the Type I flow. There are two weak recirculations trapped on either side of the heating body. They are weak because the air in this region is almost uniformly warm. This is very unusual since all the air in the lower half of the cavity is warmer than that in the upper half, yet is prevented from rising. It is trapped by the very strong recirculations of cold air above. Surprisingly, this flow pattern is steady and very stable. Heat from the sides of the hot body

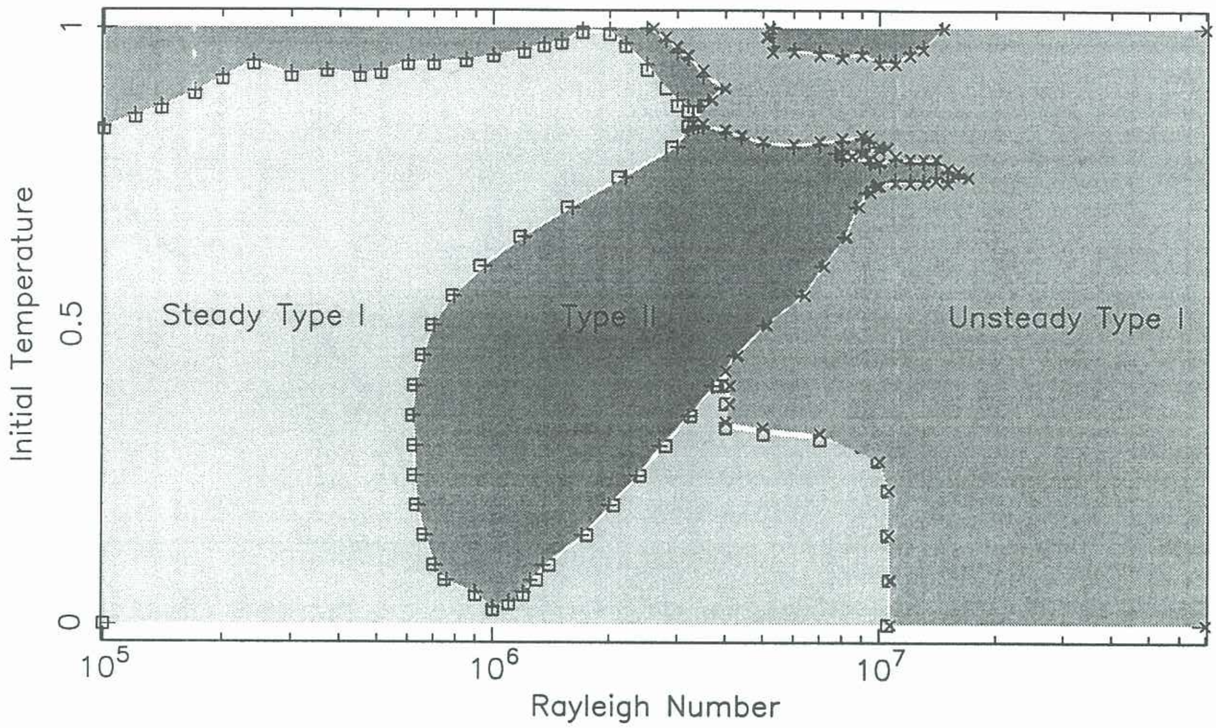

Figure 3: PHASE PORTRAIT - THE CONDITIONS FOR STEADY AND UNSTEADY TYPE I AND TYPE II FLOWS

is convected upwards by the lower recirculation into the region between the upper and lower ones. It then diffuses across into the the upper recirculation and is finally absorbed by the cold plate.

PHASE PORTRAIT

The phase portrait contains three types of regions; steady and unsteady Type I and steady Type II. The type of flow is determined entirely by the Ra and the initial temperature of the air T_0. Figure 3 shows a phase portrait of the solution space. At low Ra ($< 6 \times 10^5$), the flows are steady Type I , except for very high initial air temperatures for which the flows are steady Type II . At higher Ra, there is an abrupt transition from steady Type I to a Type II flow. The transition occurs for lower Ra at lower T_0. At higher Ra there is a transition back to Type I flows. For low T_0 these Type I flows are asymptotically steady, but for higher values of T_0 they are unsteady. At even higher Ra ($> 10^7$) all the Type I flows become unsteady. The existence of steady and unsteady branches of the solution, for the same Ra, is unexpected. Note that all the flows are steady for Ra$< 10^6$. The transition from one flow to the other is very sharp. There is no gradual change, since the two flow patterns are topologically incompatible

There are four separate mechanisms involved in the creation and destruction of these new Type II flows. This requires an understanding of the evolution of the flow. The early evolution involves diffusion of heat from the hot body into the adjacent air and the cooling of air around the plate. The hot air forms two vertical jets, one on each side of the heating body. These drive the primary recirculations that form on either side. The cold air forms a pool directly under the middle of the plate. Since the plate is not as wide as the ceiling there is curvature in the isotherms, that generates recirculations in the top corners. In general, the primary recirculations strengthen and rise higher into the cavity, dissipating the corner recirculations and the pool of cold air. A plume is then formed and a Type I flow ensues.

Mechanism 1

When the pool of cold air has grown large enough it begins to fall, forming a cold downward jet. This meets the rising hot jets. At low Ra the cold air is pushed back up and dissipated leading to a Type I flow. For a sufficiently high Ra, the jets become thin enough that the cold jet can penetrate between the hot jets and contact the hot body. The cold jet generates two small vortices between the hot body and the plate that grow and force the primary recirculations into the lower half of the cavity. This leads to a Type II flow. The first jets to touch the opposite heat source/sink grow rapidly and dominate the flow. This is determined by the relative strengths of the jets and their thicknesses, which are determined by T_0 and Ra respectively.

Mechanism 2

The main destruction mechanism involves the established cold jet becoming unstable to transverse disturbances. It then buckles and the the secondary recirculations loose contact with either the hot or cold surface and decay away, leaving the Type I flow. These mechanisms are responsible for the shapes of the left and right side of the central Type II region.

Mechanism 3

At low Ra and very high T_0 the hot jets are very weak and the corner recirculations grow unopposed and fill the upper part of the cavity. This leads to a Type II flow.

Mechanism 4

At high T_0 and high Ra, the cold air produced under the plate drops in an irregular sequence of streamers. Under the correct conditions, there are enough to merge and reinforce each other to form a stable cold downward jet.

Stability of phase portrait

The final flow pattern is a result of the complex balance between the strength of the hot and cold jets during the initial parts of the flow evolution. This balance is crucially affected by the Ra, (which determines the thicknesses of the jets) and T_0 (which determines how far the flow is from thermal equilibrium). Mechanism 1 is not sensitive to the mesh resolution. When constructing the phase portrait these parts were stationary with respect to variations in mesh size. Mechanism 2 results from instabilities in the cold central jet. Calculations involving such instabilities are much more dependent on accuracy and therefore mesh resolution. Reasonable variations were found in the location of the right boundary (where the flow changes from Type II back to Type I) when increasing the resolution from 2,000 to 3,000 corner nodes. Increasing the resolution to 4,000 corner resulted in only minor changes to the position. This mechanism is more sensitive to the mesh resolution for $T_0 < 0.5$. We used the more accurate 4,000 corner node meshes for all Ra$> 10^6$, in order to provide as much certainty as possible. Nonetheless, very minor changes to the phase portrait are possible at the higher Ra, if the resolution were increased further. Computational expense means that this is not presently feasible.

HEAT FLOW CHARACTERISTICS

The Type II pattern has a lower asymptotic Nu than the Type I flow at the same Ra. The Nu is therefore discontinuous whenever changes in Ra or T_0 cause the flow to move from one of the regions in Figure 3 to another. Figure 4 shows the variation of Nu with increasing Ra for $T_0 = 0.2$. This is equivalent to a slice through the phase portrait along $T_0 = 0.2$. Note the abrupt reduction in the Nu as the flow changes to Type II and an abrupt increase when the flow reverts to Type I. This could have important implications for some applications, such as cooling of electronic components in small enclosures.

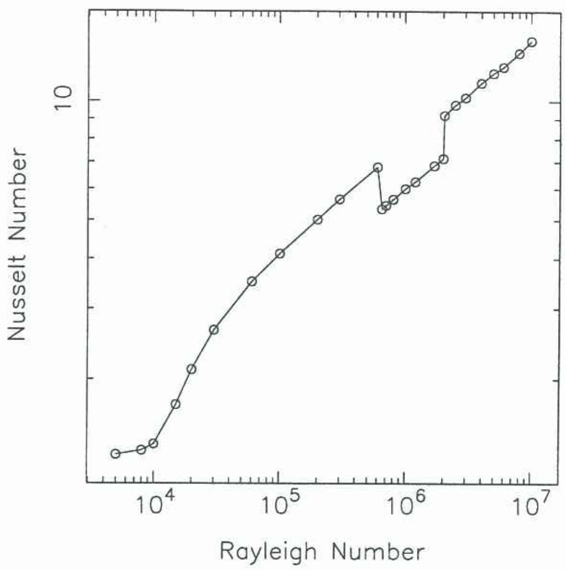

Figure 4: DISCONTINUITIES IN THE NU MARK THE ABRUPT CHANGE IN THE FLOW TYPE

The temperature distributions shown in Figures 1 and 2 are the key to the lower heat transfer in Type II flows. In the Type I flow the strong primary recirculations cause steep temperature gradients on the sides of the heating body. There is strong heat transfer here. There is relatively little heat transfer from the top. In the Type II flow most of the air in lower half of the cavity is nearly uniform in temperature. The much higher heat transfer from the top is unable to make up for the very weak heat transfer from both the sides. Whether the flow is Type I or Type II is determined early in the evolution by the interactions above the heating body. This means that the Type II flow can be produced even though it is not energetically preferred in the long term.

CONCLUSION

This geometry was found to have two distinct flow patterns based on either a hot upward plume or a cold downward jet. The solution space is complex and depends of the Ra and T_0. Four main mechanisms were identified for the creation and destruction of the Type II flow. The Type II has a lower asymptotic Nu. This causes discontinuities in the Nu vs Ra curve.

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