



h-adaptive finite element solution of high Rayleigh number thermally driven cavity problem

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Abstract *An h-adaptive finite element code for solving coupled Navier-Stokes and energy equations is used to solve the thermally driven cavity problem. The buoyancy forces are represented using the Boussinesq approximation. The problem is characterised by very thin boundary layers at high values of Rayleigh number ($> 10^6$). However, steady state solutions are achievable with adequate discretisation. This is where the auto-adaptive finite element method provides a powerful means of achieving optimal solutions without having to pre-define a mesh, which may be either inadequate or too expensive. Steady state and transient results are given for six different Rayleigh numbers in the range 10^3 to 10^8 for a Prandtl number of 0.71. The use of h-adaptivity, based on a posteriori error estimation, is found to ensure a very accurate problem solution at a reasonable computational cost.*

1. Introduction

Thermally driven cavity flow has been used to validate computer fluid flow models for the last two decades; it is also an important flow problem in its own right. Simulating a large horizontal temperature difference across a vertical cavity has applications in nuclear reactor insulation, double glazing, predicting fire spread in buildings and dispersion of heat in estuaries. The thermal cavity problem has been extensively studied and solved for Prandtl number of 0.71 (corresponding to an air filled cavity) over a range of Rayleigh numbers in a steady state (de Vahl Davis and Jones, 1983; Jones, 1979; Saitoh and Hirose, 1989; de Vahl Davis, 1983), and transient manner (Le Quere, 1991; Chenoweth and Paolucci, 1986; Paolucci and Chenoweth, 1989). Several researchers have solved this problem using $Pr = 1.0$ (Greshe *et al.*, 1979; Marshall *et al.*, 1978; Usmani, 1991); however, Patterson and Imberger (1980) determined that the steady state result is independent of the Prandtl number, but the transient behaviour, and hence the approach to steady state, is not. De Vahl Davis and Jones (1983) invited researchers to submit solutions of the thermal cavity problem using $Pr = 0.71$. A complete set of results is available for comparison of flow data at Rayleigh numbers from 10^3 to 10^6 . They concluded that, for a given problem and solution technique, mesh density controlled the accuracy of the results.

They also concluded that, although there were accurate contributions from both the FEM and FDM, the former was by and large the better, giving better results at higher Rayleigh numbers. They also recommend that further work be

conducted on the selective refinement of the mesh in the region of the boundary layers, stressing that this would be important for high Rayleigh numbers.

Finally they report that Upson *et al.*, who produced one of the best solutions, used the finite element method and had taken care to provide a high density of grid points in the wall and corner regions of the cavity.

Solutions have been obtained for Rayleigh numbers of 10^7 and 10^8 by a number of authors, for instance Saitoh and Hirose (1989), Le Quere (1991), Haldenwang (1986), Haldenwang and Labrosse (1986), Le Quere and De Roquefort (1985), but the volume of published results is considerably less than for the lower Rayleigh number cases. Solutions for Rayleigh numbers 10^3 to 10^8 will be presented in this paper and compared with the existing results.

2. Governing equations

The governing equations have been written for a constant density, incompressible Newtonian fluid using the Boussinesq approximation to model buoyancy:

Continuity

$$\nabla \cdot \mathbf{v} = 0 \quad (1)$$

where \mathbf{v} represents the velocity.

Navier-Stokes

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) + \nabla P = \nabla \cdot \mu \left[\nabla \mathbf{v} + (\nabla \mathbf{v})^T \right] - \rho \mathbf{g} \beta (T - T_r) \quad (2)$$

subject to boundary conditions:

$$\mathbf{F} = P \mathbf{n} - \mu \left[\nabla \mathbf{v} + (\nabla \mathbf{v})^T \right] \cdot \mathbf{n} \quad (3)$$

$$\mathbf{v} = \bar{\mathbf{v}}(x, y, t) \quad (4)$$

and initial conditions:

$$\mathbf{v}(t = 0) = \mathbf{v}_o \quad \text{with} \quad \nabla \cdot \mathbf{v}_o = 0 \quad (5)$$

where μ is the dynamic viscosity, \mathbf{g} is the acceleration due to gravity, β is the volumetric coefficient of thermal expansion, T is the temperature, T_r is a reference temperature, \mathbf{F} represents the applied tractions on the boundary and n is the unit normal vector.

Energy

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T = \nabla \cdot \kappa \nabla T \quad (6)$$

subject to boundary conditions:

$$\mathbf{n} \cdot (\kappa \nabla T) = q \quad (7)$$

$$T = \bar{T}(x, y, t) \quad (8)$$

and initial conditions:

$$T(t = 0) = T_o \quad (9)$$

where q is a specified normal heat flux and κ is the thermal diffusivity given by:

$$\kappa = \frac{k}{\rho C_p} \quad (10)$$

where k is the thermal conductivity, ρ is the fluid density and C_p is the specific heat capacity.

Finite element formulation

The program is based on the Galerkin Finite Element Method (GFEM), solving for the primitive variables: U-velocity, V-velocity and T-temperature at all nodes in the mesh and P-pressure at a reduced level of interpolation to avoid spurious pressure modes, using a mixed formulation for the Navier-Stokes equations. The Navier-Stokes and energy equations were coupled by the Boussinesq approximation for buoyancy. Notation used here is as used by Gresho *et al.* (1979, 1980). The Galerkin FEM discretisation produces a system of ODEs as follows:

Navier-Stokes

$$\begin{bmatrix} \mathbf{M}_u & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \mathbf{M}_v \end{bmatrix} \begin{pmatrix} \dot{\mathbf{u}} \\ \dot{\mathbf{P}} \\ \dot{\mathbf{v}} \end{pmatrix} + \begin{bmatrix} \mathbf{K}_{uu} & \mathbf{C}_u & \mathbf{K}_{uv} \\ \mathbf{C}_u^T & 0 & \mathbf{C}_v^T \\ \mathbf{K}_{vu} & \mathbf{C}_v & \mathbf{K}_{vv} \end{bmatrix} \begin{pmatrix} \mathbf{u} \\ \mathbf{P} \\ \mathbf{v} \end{pmatrix} = \begin{pmatrix} F_u \\ 0 \\ F_v \end{pmatrix}.$$

The first to third rows represent the x -momentum, continuity and y -momentum equation respectively. The right-hand side vector \mathbf{F}_v contains the coupling buoyancy term.

Energy

$$[\mathbf{M}_T](\dot{\mathbf{T}}) + left[\mathbf{K}_T](\mathbf{T}) = (\mathbf{F}_T).$$

Expansion of all terms can be found in Usmani *et al.* (1992). The two systems of equations above are solved as a coupled system, with the \mathbf{K}_T term containing the velocities (obtained from solving the flow field) and the \mathbf{F}_v term containing the buoyancy forces (determined by the temperature field).

Temporal discretisation

Temporal discretisation of the time domain is achieved by applying the generalised midpoint rule (Hughes, 1983, 1987):

$$\left[\frac{\mathbf{M}_{n+\alpha}}{\alpha \Delta t} + \mathbf{K}_{n+\alpha} \right] (\theta_{n+1}) = \left[\frac{\mathbf{M}_{n+\alpha}}{\alpha \Delta t} - \frac{(1-\alpha)}{\alpha} \mathbf{K}_{n+\alpha} \right] (\theta_n) + \frac{(\mathbf{F}_{n+\alpha})}{\alpha} \quad (11) \quad h\text{-adaptive finite element solution}$$

Variation of α leads to different members of this family of methods, i.e.

$\alpha = 0$ – forward difference or forward Euler.

$\alpha = \frac{1}{2}$ – midpoint rule or Crank Nicolson.

$\alpha = \frac{2}{3}$ – Galerkin.

$\alpha = 1$ – backward difference or backward Euler.

The Crank Nicolson, Galerkin and backward Euler schemes are all unconditionally stable; however, of these methods the oscillation limit is lowest for $\alpha = \frac{1}{2}$. A larger time step size chosen for $Ra \rightarrow 10^3$ to 10^7 constrains the choice of α to $\frac{2}{3}$. The time step size for $Ra = 10^8$ is chosen to be small enough to avoid an oscillatory solution when using $\alpha = \frac{1}{2}$. The choice of unconditionally stable implicit methods is enforced by the use of h -adaptivity as the smallest elements determine the stability of conditionally stable explicit methods, which makes them impractical for use in this context.

The formulations described above were implemented in the implicit transient FE code CADTRAS (Coupled Advective Diffusive TRANsport model), which was used to solve the thermally driven cavity problem. The code incorporates an unstructured Delaunay triangulation based mesh generator (Huang and Usmani, 1994), which allows automatic adaptive re-meshing to take place at each time step if necessitated by the a posteriori error estimation algorithm. Six-node triangular elements are used for all the meshes.

3. Adaptivity

The use of h -adaptivity enables the solution of this problem at high Rayleigh number without the necessity of designing a suitable mesh at first and going through a trial-and-error process. Adaptivity automatically produces an optimal mesh based on a user specified discretisation error, thus saving computational time and focusing intelligently over successive time steps on areas of high scalar gradients (which for this problem coincide with the areas of high velocity gradients).

There are five distinct steps to the iterative adaptive process used here:

- (1) Solution of the coupled system.
- (2) Recovery of smoothed scalar gradients using the super-convergent patch recovery (SPR) method (Zienkiewicz and Zhu, 1991).
- (3) Error estimation using the a posteriori error calculated at all nodes in the mesh for the scalar field.
- (4) Re-meshing based on the mesh sizes produced from the previous step.
- (5) Transfer of all data to the new mesh.

Recovery

The temperature field generated by the finite element method is most accurate at nodal points, whereas the temperature gradients are most accurate at Gaussian integration points, known as the super-convergence phenomenon. Hinton and Campbell (1974) showed that finite elements produce superior values of temperature gradient at node points after application of a smoothing procedure. Their method was based on a global smoothing scheme requiring the solution of a large system of equations. A more efficient and effective procedure was introduced by Zienkiewicz and Zhu (1991), called super-convergent patch recovery (SPR). The smoothed nodal gradients are calculated from the Gauss points on a patch of elements surrounding a node, using a least squares interpolation, for each node in the mesh.

Error estimation

The error estimator used was originally derived for heat conduction (Lewis *et al.*, 1991). Mathematical justification of using such an estimator for the problem of this paper does not exist; however, as the estimator used is based on the scalar flux, it has proven very effective in detecting regions of high scalar gradient, which in practice is sufficient for the purposes of this paper. The a posteriori error is based upon an energy norm (see Zienkiewicz and Zhu, 1987):

$$\|e\|^2 = \int_{\Omega} (\nabla T)^T \kappa \nabla T d\Omega - \int_{\Omega} (\nabla \hat{T})^T \kappa \nabla \hat{T} d\Omega \quad (12)$$

If we define

$$\begin{aligned} \|Q\|^2 &= \int_{\Omega} (\nabla T)^T \kappa \nabla T d\Omega \\ \|\hat{Q}\|^2 &= \int_{\Omega} (\nabla \hat{T})^T \kappa \nabla \hat{T} d\Omega \end{aligned} \quad (13)$$

then equation (12) can be rewritten as

$$\|e\|^2 = \|Q\|^2 - \|\hat{Q}\|^2. \quad (14)$$

Such a definition allows a practical representation of the error norm in terms of a percentage error η ,

$$\eta = \frac{\|e\|}{\|Q\|} \times 100\%. \quad (15)$$

Re-meshing and mesh generation

Specification of a permissible error $\bar{\eta}$ determines the level of refinement throughout the mesh, leading to a predicted reduction or increase in the element sizes so that the new mesh may possess an approximately equal distribution of

error. The maximum permissible error for each element is calculated as:

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element solution

$$\|\hat{e}\|_e = \bar{\eta} \left(\frac{\|Q\|^2}{m} \right)^{\frac{1}{2}} \quad (16)$$

where m is the number of elements, $\bar{\eta}$ is the specified maximum percentage error. Dividing $\|\hat{e}\|_e$ by the calculated error in an element yields a parameter ξ_e as follows:

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$$\xi_e = \frac{\|e\|_e}{\|\hat{e}\|_e} \quad (17)$$

i.e. if $\xi_e > 1$ the mesh must be refined in the vicinity of element e ; conversely, if $\xi_e < 1$ the mesh may be coarsened. The new element size is calculated using

$$\bar{h}_e = \frac{h_e}{\xi_e^{\frac{1}{p}}} \quad (18)$$

where h_e is the original element size and p is the order of the element shape functions.

Mesh data transfer

Ensuring proper transfer of variables between meshes is crucial for conservation of quantities such as energy and momentum. A transfer strategy using local coordinates of nodal points and elemental shape functions has been used that maps the mesh data accurately. The local coordinates ($\xi - \eta$) of each node in the adapted mesh are determined with respect to the elements of the previous mesh. Element shape functions are then used to interpolate the data on to the new mesh nodes.

4. The thermally driven cavity benchmark problem

The problem involves modelling fluid flow in a two-dimensional square cavity of typical dimension L with the two vertical walls being maintained at a temperature difference of ΔT (see Figure 1). The top and bottom walls are insulated and the velocities at all boundaries set to zero. The fluid inside the cavity is initially at rest and at a temperature which is the mean of the temperatures on the vertical walls.

The steady state flow and heat transfer in the thermal cavity are characterised by the Rayleigh number:

$$Ra = g\beta \frac{\Delta TL^3}{\nu\kappa}. \quad (19)$$

The following non-dimensional groups are used in the analysis and presentation of the computational results:

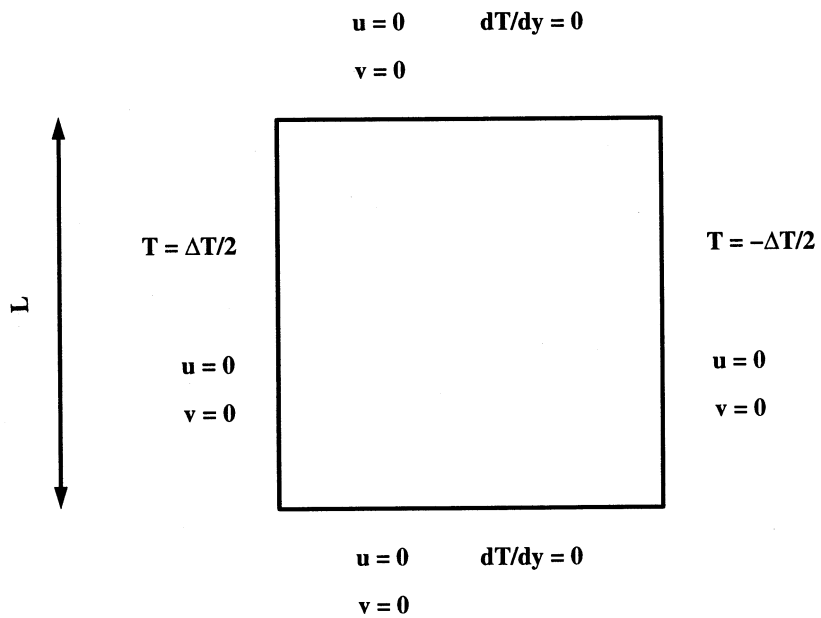


Figure 1.
Boundary conditions for
thermal cavity
benchmark problem

Velocity

$$u^* = \frac{uL}{\kappa} \tag{20}$$

$$v^* = \frac{vL}{\kappa} \tag{21}$$

Temperature

$$T^* = \frac{T - T_2}{T_1 - T_2} \tag{22}$$

Coordinates

$$x^* = \frac{x}{L} \tag{23}$$

$$y^* = \frac{y}{L} \tag{24}$$

Time

$$t^* = \frac{\kappa t}{L^2} \tag{25}$$

where * indicates the non-dimensional quantity. T_1 and T_2 are the fixed temperatures at the two side walls of the cavity.

The Nusselt number is calculated at each node in the domain using

$$Nu = uT - \frac{\partial T}{\partial x} \quad (26)$$

where the temperature gradient is obtained by the gradient recovery process.

Results

The spacing between the isotherms at the sides of the cavity decreases with increasing Rayleigh number. The high level of mesh refinement in this area allows the thin boundary layer to be captured accurately, avoiding any oscillations that can be generated when modelling steep temperature gradients without adequate discretisation. A uniformly distributed mesh with the “same” number of elements will be inadequate to model large changes in temperature at the boundary and will produce an oscillatory solution. At high Rayleigh numbers ($> 10^6$) a convergent solution may not be possible at all. Figure 2

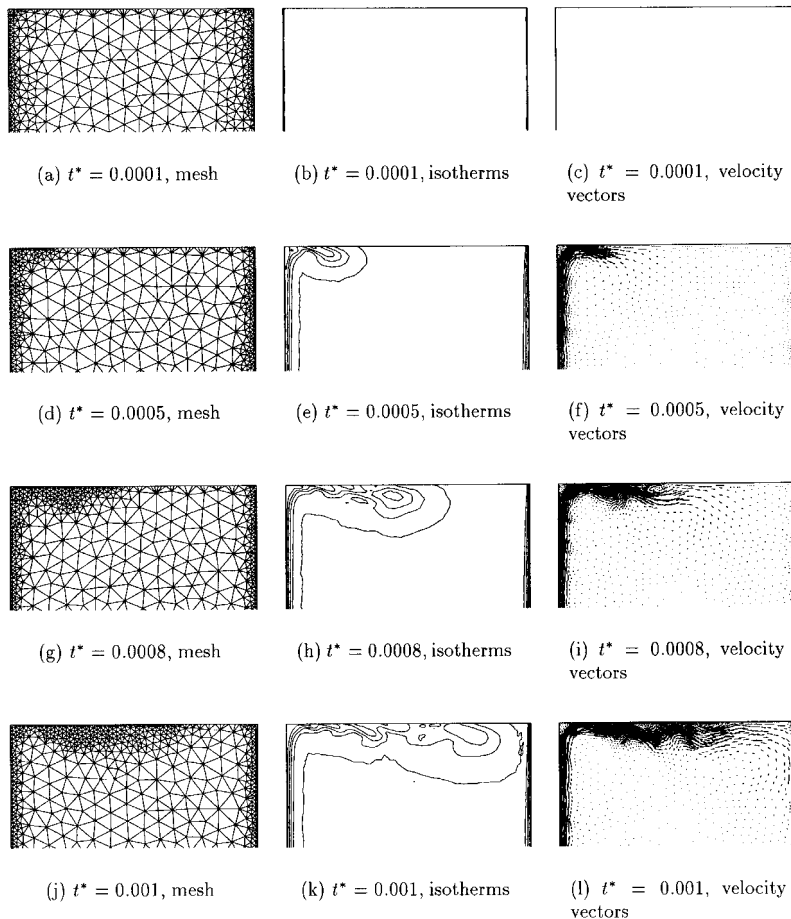


Figure 2.
Mesh development for
 $Ra = 10^8$

shows the top half of the cavity for four different dimensionless times. It can be seen that the mesh adapts to follow the high temperature gradient front as it passes the departing corner. The refinement of the mesh around the side walls at $t = 0.0001$ (Figure 2(a)) is due to a pre-adaptive loop where the mesh is refined based on the initial conditions.

Figure 3 shows plots of velocity and temperature along the centre line of the cavity ($y = 0$) for each Rayleigh number at steady state. The Figure clearly shows that mesh refinement based only upon the temperature gradients is appropriate for this problem as the steep velocity gradients occur in the same locations as the steep temperature gradients.

Figures 4-9 show the mesh, velocity vectors, pressure field and isotherms for each Rayleigh number at steady state.

The parameters presented are described in Table I:

$$Ra \rightarrow 10^3 \text{ to } 10^6.$$

Table II shows results obtained for the six Rayleigh numbers investigated.

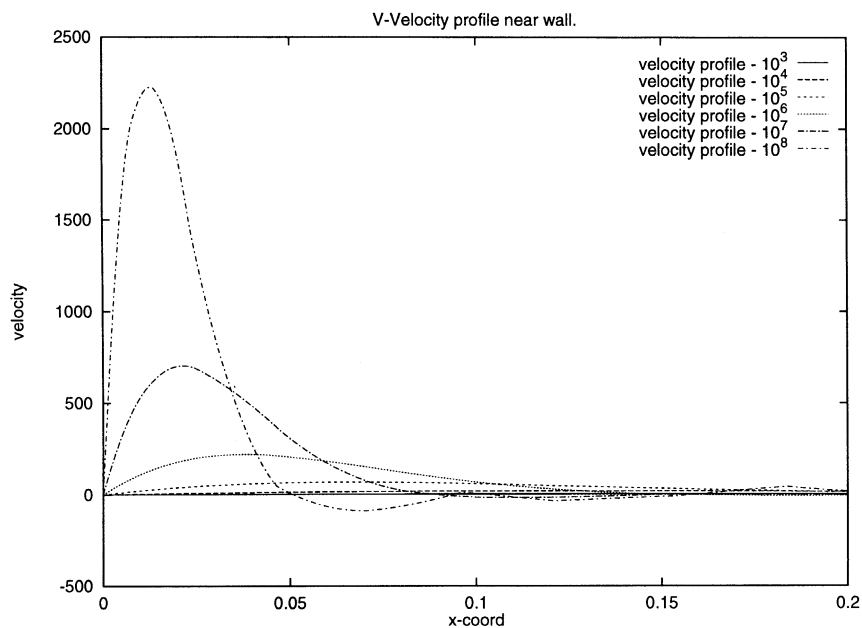
The results for all the values measured are very close to the accurate results obtained by De Vahl Davis (1983), only deviating slightly at 10^6 . The error between De Vahl Davis' solution and the adaptive FEM results have been calculated and presented in Table III, in the manner presented in de Vahl Davis and Jones (1983):

$$Ra \rightarrow 10^7 \text{ to } 10^8.$$

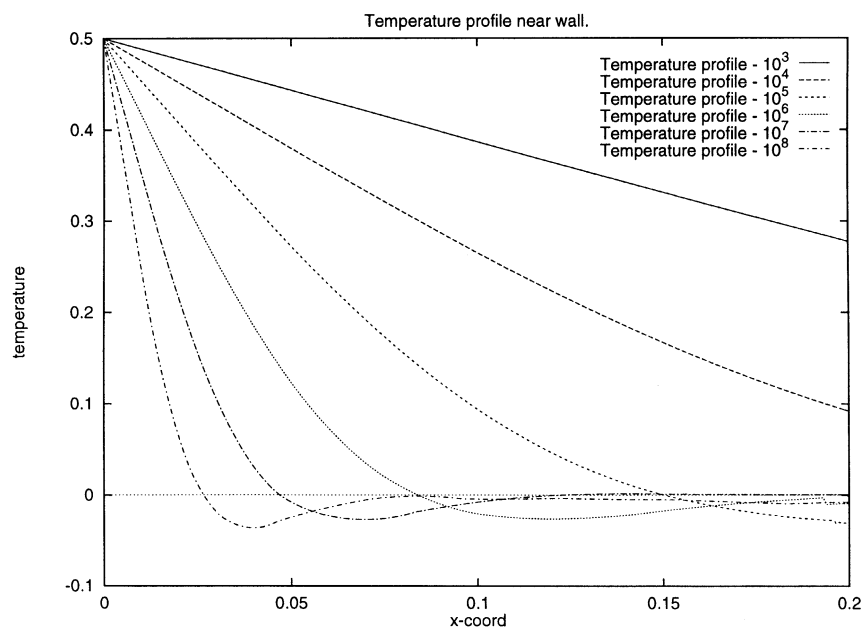
Established benchmark solutions analogous to the lower Rayleigh number results do not exist for the higher Rayleigh number problems. However, several researchers have solved the thermally driven cavity problem for 10^7 and above. Table IV shows the comparison of the adaptive FEM results with others for the Rayleigh number of 10^7 . Again, the adaptive FEM results compare well with other solutions both in the magnitude of velocity and heat transfer rates and with the locations of the maximum and minimum values. A similar comparison is shown in Table V for Rayleigh number 10^8 ; the same conclusions apply.

6. Conclusion

A full set of results have been produced for the thermally driven cavity problem at Rayleigh numbers of 10^3 to 10^8 . The use of h -adaptivity ensures a very accurate solution to this problem at a reasonable computational cost. A pre-adaptive step, adapting the mesh on the basis of the fixed temperature boundary conditions, allows the thin boundary layers to be captured effectively from the very beginning. The results presented compare well with existing transient and steady state solutions both qualitatively and quantitatively. For highly advection dominated problems, such as the high Rayleigh number cases of the thermally driven cavity, h -adaptivity fulfils another very important function, in addition to the vital task of providing optimal meshes. This



(a) Plot of velocity on $y = 0.5$ near boundary



(b) Plot of temperature on $y = 0.5$ near boundary

Figure 3.
Velocity and
temperature near the
vertical boundary

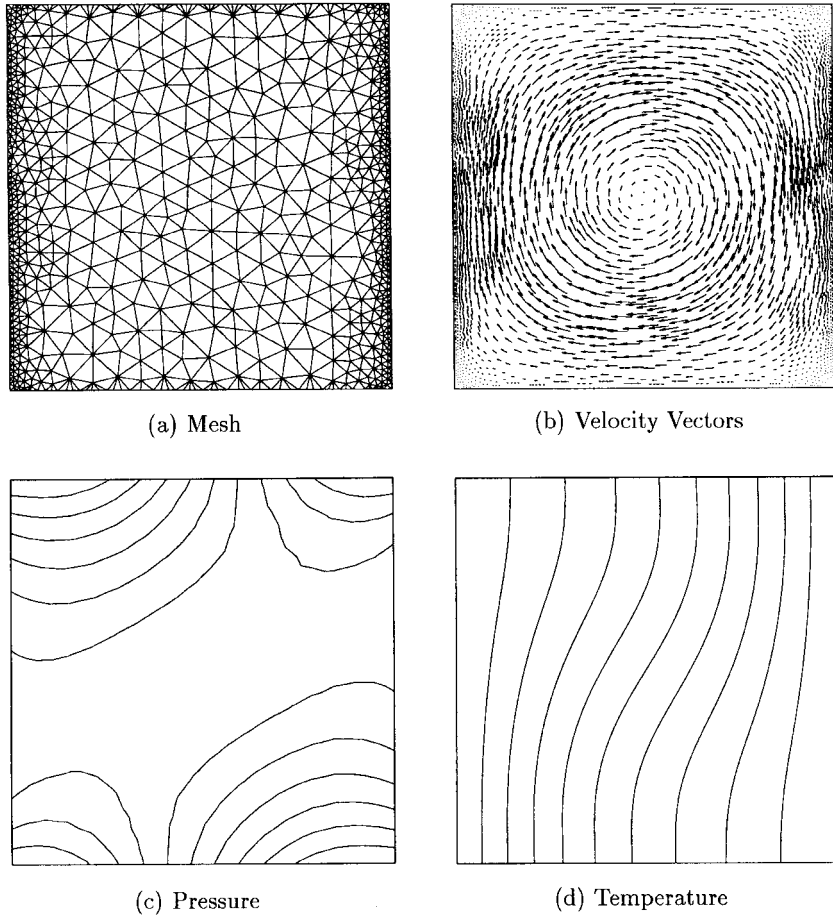


Figure 4. Mesh, velocity vector plot, temperature contours and pressure contours for a Rayleigh number of 10^3

Parameter	Description
U_{\max}	Maximum horizontal velocity on vertical mid-plane of cavity
y	y -coordinate position of maximum horizontal velocity on vertical mid-plane
V_{\max}	Maximum vertical velocity on horizontal mid-plane of cavity
x	x -coordinate position of maximum vertical velocity on horizontal mid-plane
Nu_0	Average Nusselt number on the vertical boundary $x = 0$
Nu_{\max}	Maximum Nusselt number on the vertical boundary $x = 0$
y	y -coordinate position of maximum Nusselt number on vertical boundary $x = 0$
Nu_{\min}	Minimum Nusselt number on the vertical boundary $x = 0$
y	y -coordinate position of minimum Nusselt number on vertical boundary $x = 0$

Table I. Measured parameters

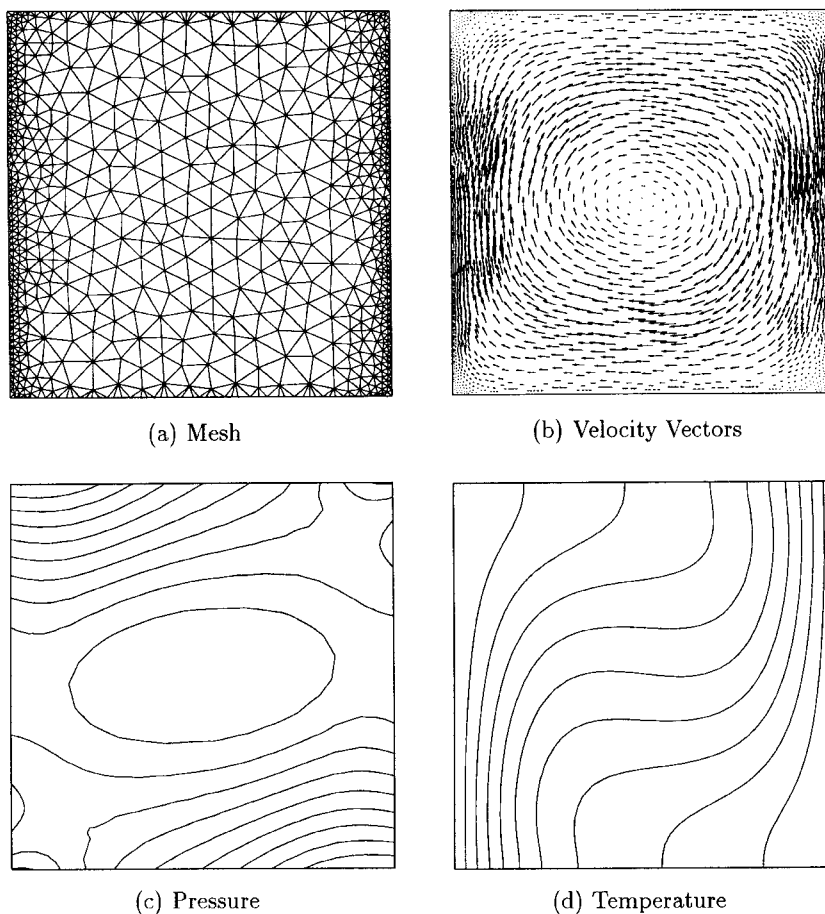


Figure 5.
Mesh, velocity vector
plot, temperature
contours and pressure
contours for a Rayleigh
number of 10^4

	10^3	10^4	10^5	10^6	10^7	10^8
U_{\max}	3.6493	16.1798	34.7741	64.6912	145.2666	283.0689
y	0.8125	0.8235	0.8535	0.8460	0.8845	0.9455
V_{\max}	3.6962	19.6177	68.6920	220.8331	703.2526	2,223.4424
x	0.1790	0.1195	0.0665	0.0380	0.0215	0.0130
Nu_0	1.1149	2.2593	4.4832	8.8811	16.3869	29.6256
Nu_{\max}	1.5062	3.5305	7.7084	17.5308	41.0247	91.2095
y	0.08956	0.1426	0.08353	0.03768	0.03899	0.0670
Nu_{\min}	0.6913	0.5850	0.7282	0.9845	1.3799	2.0440
y	1.0	1.0	1.0	1.0	1.0	1.0

Table II.
The benchmark
solution

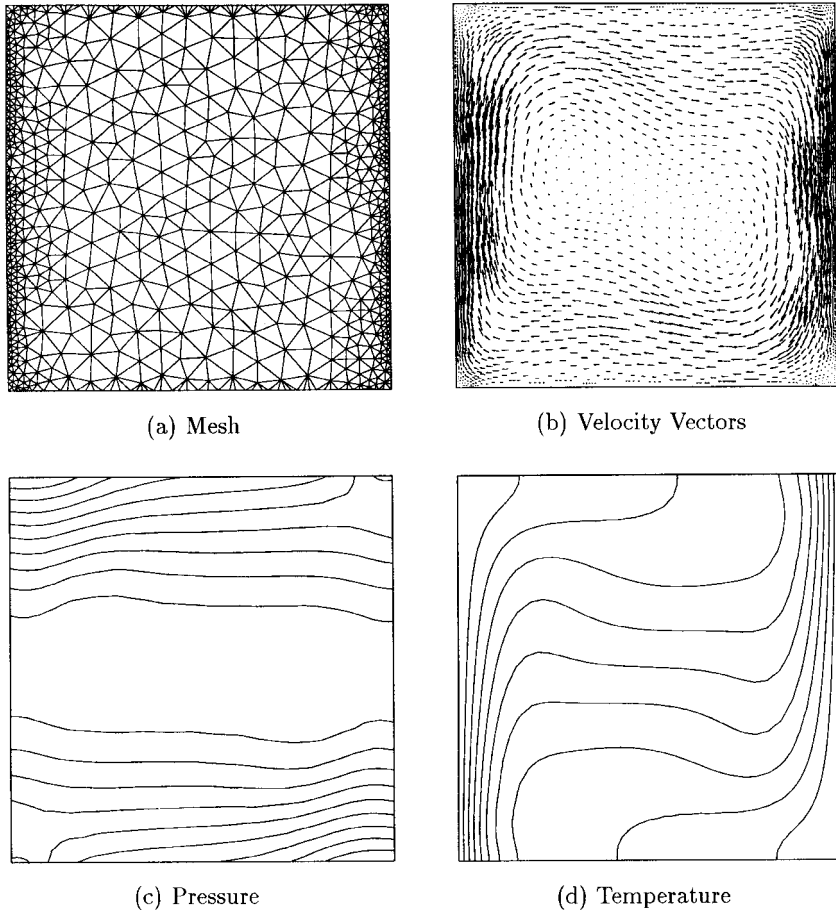


Figure 6. Mesh, velocity vector plot, temperature contours and pressure contours for a Rayleigh number of 10^5

	10^3	10^4	10^5	10^6
U_{\max}	0.0	0.0	-0.1	-0.1
V_{\max}	0.0	0.0	-0.1	-0.7
Nu_0	0.2	-1.0	0.6	-0.7
Nu_{\max}	-0.1	-0.1	0.1	2.2
Nu_{\min}	0.1	0.2	0.1	0.5

Table III. Solution error (%)

function is related to the deficiency of standard Galerkin finite element method (analogous to centred difference FDM) in solving flow and transport problems where advection is the dominant mechanism. Many special techniques exist in order to address this deficiency, such as the SUPG method (Brooks and Hughes, 1982) and the Taylor-Galerkin method (Donea, 1984). However, Gresho and Lee (1981) have shown that the oscillations that result from using GFEM in

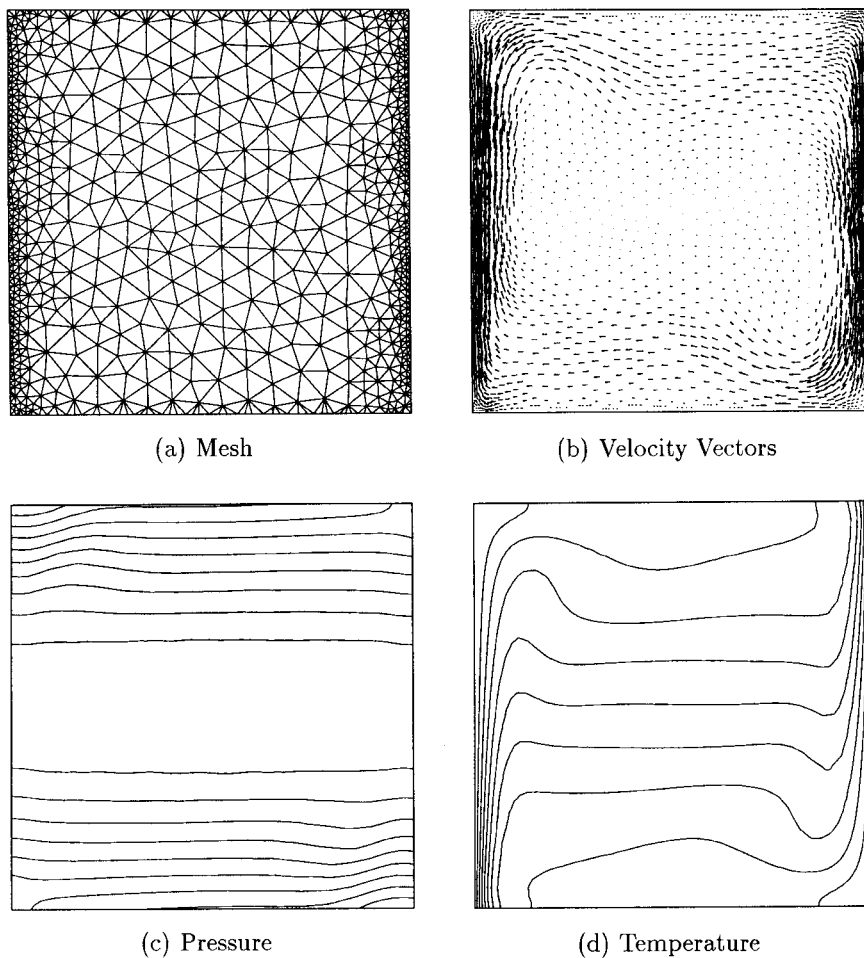


Figure 7.
Mesh, velocity vector
plot, temperature
contours and pressure
contours for a Rayleigh
number of 10^6

	Present work	Haldenwang (1986)	Le Quere (1991)	Chenoweth (1986)	Le Quere (1985)
U_{\max}	145.26	381.6	148.6	146	148.8
y	0.8845		0.879	0.881	0.879
V_{\max}	703.2526	700.4	699.1	699	699.3
x	0.0215		0.021	0.0213	0.0213
Nu_0	16.3869	16.53	16.523	16.82	16.51
Nu_{\max}	41.0247		39.39		39.37
y	0.03899		0.018		0.0180
Nu_{\min}	1.3799		1.36635		1.367
y	1.0		1.0		1.0

Table IV.
The benchmark
solution for $Ra = 10^7$

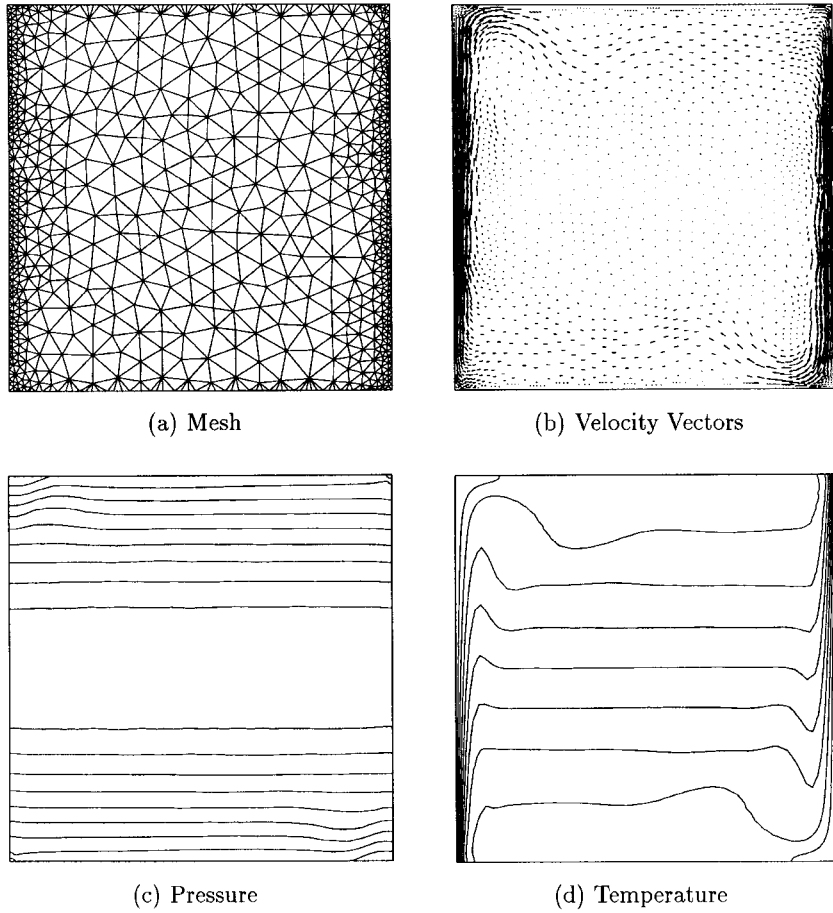


Figure 8. Mesh, velocity vector plot, temperature contours and pressure contours for a Rayleigh number of 10^7

	Present work	Haldenwang (1986)	Le Quere (1991)
U_{\max}	283.0689	1,082	321.9
y	0.9455		0.928
V_{\max}	2,223.4424	2,192	2,222
x	0.0130		0.012
Nu_0	29.6256	30.26	30.225
Nu_{\max}	91.2095		87.2355
y	0.0067		0.008
Nu_{\min}	2.0440		1.91907
y	1.0		1.0

Table V. The benchmark solution for $Ra = 10^8$

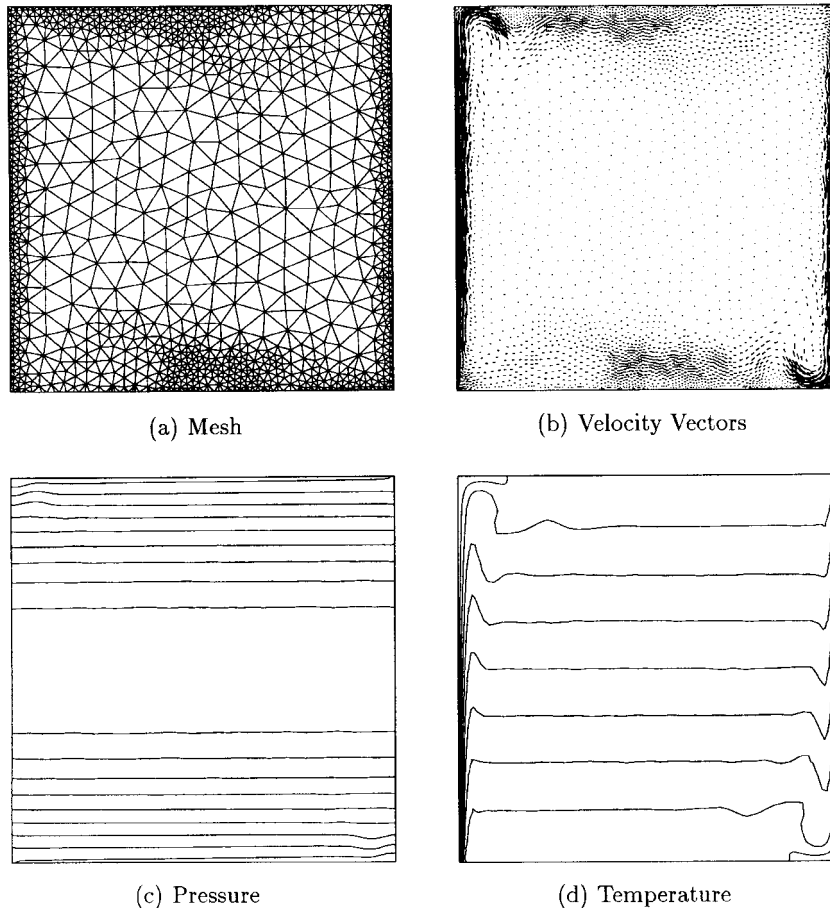


Figure 9.
Mesh, velocity vector
plot, temperature
contours and pressure
contours for a Rayleigh
number of 10^8

advection dominated problems are strongly related to inadequate spatial discretisation. Usmani (1999) showed conclusively that for transient solution of advection dominated problems this was indeed the case and the discretisation produced by using *h*-adaptivity made it unnecessary to use any special schemes for advection dominant problems. This finding is confirmed by the results of this paper, where all results have been produced using simply honest GFEM. In the opinion of the authors, this fact makes it doubly attractive to use this method.

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