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AN INTERFEROMETRIC INVESTIGATION OF NATURAL CONVECTION IN A PARTIALLY OPENED ENCLOSURE WITH A DISCRETE HEAT SOURCE

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Natural convection in an enclosure with an opening in the right vertical wall and a heat source on the bottom surface was investigated using a holographic interferometric technique. In particular, emphasis was placed on the effects caused by changing the opening length, divider height, and heat source temperature. When the enclosure was partially opened, warm air from inside escaped from the upper part of the opening and was replaced by surrounding air, which flowed into the enclosure from the lower part of the opening. The flow rates of inflow and outflow through this opening increased with larger opening length, smaller divider height, and higher heater temperature. When the opening length was small, the opening did not significantly affect the upward flow of warm air from the heater, and resulted in a symmetrical temperature distribution. The divider prevented the development of upward flow from the heat source such that the temperature in the absence of a divider was generally higher than that for the longest divider. For cases with a large opening length, the upward flow was forced to move into the enclosure's left-hand side by the increased inflow. The effect of the divider height was not significant due to the increased flow rates through the increased opening length. The temperatures achieved with the longest divider were a little higher than those for the other cases due to the lower cold flow rate and the blocking of the cold air inflow by the longest divider.

The study of natural convection from a discrete heat source in a vented enclosure has a number of engineering applications such as cooling of electronic components, fires in compartments, and ventilation through openings connecting rooms in buildings. Natural-convection air cooling of electronic components in a vented enclosure is frequently employed in systems using low-heat-generating electronic devices such as compact power supplies and portable computers, due to simplicity of design, low installation and maintenance cost, absence of noise, and high reliability. Yu and Joshi [1] conducted a three-dimensional numerical investigation of steady natural convection in vented enclosures. A discrete flush-mounted heat source on a vertical substrate was used to simulate a heat-generating electronic component and the effects of vent location and size were examined. They also investigated combined conduction, natural convection, and radiation in vented enclosures with a special focus on the effect of radiation [2]. In their continued

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NOMENCLATURE

H	test section height, m	W	test section width, m
k	thermal conductivity, W/m K	λ	wavelength of light, nm
K	Gladstone-Dale constant, m^3/kg	ρ	gas density, kg/m^3
L	length of test section along the optical axis, m	Φ	phase difference
n	refractive index	**Subscripts**	
N	fringe number	d	divider
Ra	Rayleigh number ($= g\beta\ \Delta T H^3/v\alpha$)	h	heater
T	temperature, $^\circ$C	o	opening
ΔT	difference between heat source and room temperature, $^\circ$C		

investigation [3], the effects of varying heat source power levels, opening size, aspect ratio, and vent configurations were studied experimentally by temperature measurements and flow visualization.

In compartment fires, a countercurrent flow of outflowing hot combustion products and inflowing fresh air is established within vents. Myrum [4] conducted an experimental study of the heat transfer from a heat source located at the bottom surface of a top-vented enclosure and the resulting fluid flow through the vent opening. Flow visualization experiments revealed an unstable flow pattern in the vicinity of the vent that fluctuated in a nonperiodic manner among four basic flow modes. Epstein [5] predicted the maximum possible steady-state combustion rate within a roof-vented enclosure by considering available empirical correlations to combined natural convection and forced flow through opening in the ceiling. Kim et al. [6] investigated natural convective flow and heat transfer characteristics numerically in a partially opened enclosure with a lower, hot horizontal wall, an upper, cold partially open horizontal wall, and a horizontal divider. Son [7] simulated numerically the combined natural convection and radiation in a partially opened enclosure with a heat source. The fluid inside an enclosure was considered as an absorbing, emitting, and anisotropic scattering medium. Son showed that the location of the heat source and the length of open area significantly affected the fluid circulation and heat transfer. With an increase in the size of the opening, the inflow of cold fluid and flow circulation increased. Chu [8] investigated both experimentally and numerically the flow field created by a fire in a partially open enclosure. In his numerical work the fire is considered as a heat source, and he compared the results of pure convection case with that of a combined heat transfer case. In his experiments, real fires of combustible materials were located at the enclosure's bottom center, and flow visualization, temperature measurements, and measurements of gas concentrations were conducted.

Even though some relevant researches on the natural convection from a heat source in a vented enclosure have been conducted, as mentioned above, there still exists some lack of understanding of the flow and heat transfer characteristics occurring inside a vented enclosure. In this study the whole temperature field formed by natural-convection heat transfer in an enclosure with an opening in the right vertical wall and a heat source at the bottom surface is recorded using a holographic interferometric technique. The effects of the opening length, length of a divider attached to the top wall, and temperature of the

heat source on temperature distribution inside the enclosure are examined by analyzing fringe images.

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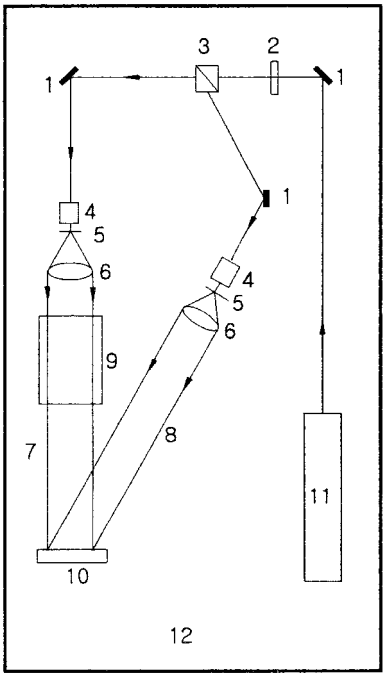
EXPERIMENTAL APPARATUS AND METHODOLOGY

Experimental System

Figure 1 shows the schematic layout of the holographic interferometry system used in this study. The light from a 30-mW He-Ne laser was separated by a polarizing, variable beamsplitter which divided the beam into reference and object beams. The beam intensity was adjusted by this variable beamsplitter to achieve a reference-to-object beam intensity ratio of approximately 1.5 to 1. Each beam was expanded and collimated into a plane wave of 10 cm diameter by a Keplerian-type beam expansion method, which uses a 10-μm pinhole, a microscope objective, and a convex lens to eliminate inherent noise. The object beam passed through the test section and was then intercepted at the holographic



1. Mirror
2. Shutter
3. Variable beamsplitter
4. Microscope objective
5. Pinhole
6. Collimating lens
7. Objective beam
8. Reference beam
9. Test section
10. Holographic plate
11. He-Ne laser
12. Optical table

Figure 1. Schematic layout of the holographic interferometry system.

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glass plate. The reference beam was at an angle of 23° relative to the normal of the holographic plate. The difference of path lengths between object and reference beams was minimized to guarantee good interference of both beams irrespective of coherent length of lasers.

A schematic diagram of the test section for natural convection is shown in Figure 2. All the walls, except the floor, are 10 mm thick and were made from bakelite (k = 1.4 W/m K), due to its low thermal conductivity. The floor was made from a ceramic board (k = 0.093 W/m K) due to its high insulation property. This ceramic board prevented heat conduction from a heat-generating source to the side walls. The square enclosure was 58 mm high (H) and 58 mm wide (W) and was 500 mm long (L). This length was considered to be long enough to ensure the assumption of two-dimensional characteristics. There was an opening of either $0.22H$ or $0.46H$ length at the right vertical wall. A divider of either $0.22H$ or $0.46H$ length and 10 mm thick was attached to the top wall center. Air temperatures inside the test section were measured directly using bead K type thermocouples, which were inserted at the half-length of the test section, through the left vertical wall, at heights of $0.25H$, $0.5H$, $0.75H$, and through the top wall at $0.75W$. All electric signals from these thermocouples were processed by a data collector and saved on a personal computer. Exact locations of all thermocouples were identified from CCD camera images using image processing software.

The heat source was a 12-mm-square column made from SK45C (k = 30.54 W/m K), a kind of special steel (composed mainly of 38% C, 22% Si, 34% M, and small amounts

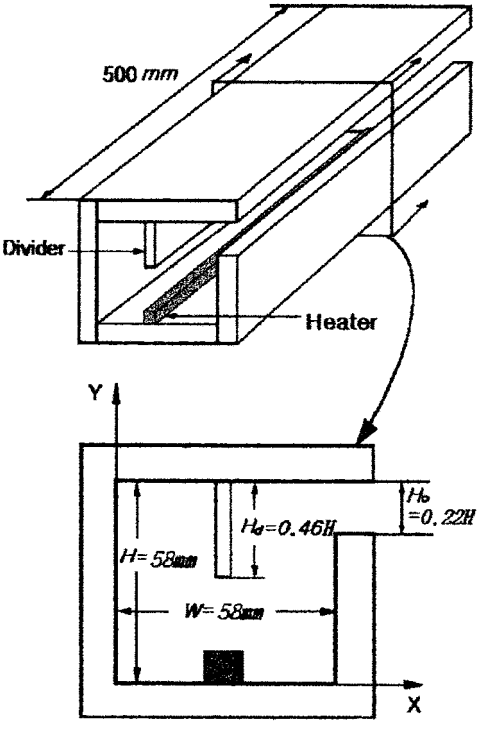

Figure 2. Schematic diagram of the test section.

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of P and S). It was heated by a 6.25-mm-diameter, 900-W cartridge heater. This cartridge heater was press-fitted through the center of the square column. AC power was supplied to the heater. The heat source was controlled by a temperature controller, which adjusted AC power to the heater according to a preset temperature value. The temperature of the heat source was measured using K-type thermocouples that were fixed to five points of the heat source surface. During the course of the experiments the temperature of the heat source remained within $\pm 0.2^{\circ}$C of its set-point value.

Experimental Procedure and Test Conditions

The holographic interferograms were obtained by a double-exposure method. The first exposure was recorded just before the start of heating and the same film was exposed again 2 h later. This 2 h was considered to be enough time for the flow field to reach steady state. Exposure duration for each pulse was 0.25 s. This duration was found from a trail-and-error method for the best quality of fringe images. The exposed hologram was processed by normal hologram processing procedures. After chemical processing the hologram was replaced onto the recording position for reconstruction. The fringe images were formed at a diffuser screen that was placed at the back of the hologram and for further analysis the images were recorded using either a CCD or a standard camera.

The parameters changed in this study were the opening length in the right vertical wall, H_o, divider length from the top center wall, H_d, and heat source temperature, T_h. The test conditions are summarized in Table 1. Air temperature before heating started ranged from 17.5 to 18.3°C. The dimensionless parameter, Ra, which is commonly used for characteristics of natural convection, was based on the side length of the enclosure as the characteristic length of the test section. The range of Ra covered in this study was from 5.42×10^5 to 7.55×10^5.

Fringe Analysis [9]

Once the temperature of any arbitrary point inside the enclosure is measured by a thermocouple, the temperature distribution of the complete enclosure can be determined using the following procedure. From the Gladstone-Dale equation [9], which relates

Table 1. Test conditions

Case	H_o (mm)	H_d (mm)	ΔT (°C)	T_h (°C)	Ra
1	12.75, 0.22H	0	22.5	40	6.54×10^5
2	12.75, 0.22H	12.75, 0.22H	22.4		
3	12.75, 0.22H	26.7, 0.46H	21.8		
4	26.7, 0.46H	0	22.0		
5	26.7, 0.46H	12.75, 0.22H	22.2		
6	26.7, 0.46H	26.7, 0.46H	21.7		
7	26.7, 0.46H	0	12.0	30	5.42×10^5
8			31.8	50	7.55×10^5

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density to the refractive index, the difference of refractive index between two neighboring fringes is expressed as

$$n_i - n_{i-1} = K(\rho_i - \rho_{i-1}) \tag{1}$$

where K, the Gladstone-Dale constant at $\lambda = 632.8$ nm, is 0.2266×10^{-3} m^3/kg for air at 288 K and 0.1013 MPa. The optical path length difference between the first and second exposures of light traveling through the test section along the optical axis is

$$\Phi = (N_i - N_{i-1})\lambda = L(n_i - n_{i-1}) \tag{2}$$

Combining Eqs. (1) and (2), we obtain

$$N_i - N_{i-1} = K\frac{L}{\lambda}(\rho_i - \rho_{i-1}) \tag{3}$$

The density of a gas in Eq. (3) can be related to temperature using the ideal gas equation of state, so Eq. (3) can be expressed as

$$N_i - N_{i-1} = K\frac{L}{\lambda}\frac{PM}{R}\left(\frac{1}{T_i} - \frac{1}{T_{i-1}}\right) \tag{4}$$

Equation (4) relates fringe numbers with temperature. If the temperature of fringe $i - 1$ is found, then the temperature of the next fringe can be determined.

The measurement uncertainty is caused mainly by air temperature measurements by thermocouples and the propagation of this error source to the temperature of the next fringe by Eq. (4). As for the uncertainty of air temperature measurements, the probe accuracy of K-type thermocouple is $\pm$ 1.1–2.2°C and the temperature accuracy of the Hewlett-Packard 34970A Data Acquisition System is $\pm$ 0.5–0.75°C according to the manufacturer's manual. Therefore, the uncertainty of air temperature measurements due to the above two error sources is $\pm$ 1.21–2.32°C by the root-sum-square method. The uncertainty of temperature measurements including the propagation of air temperature measurements is $\pm$ 1.198–2.297°C.

EXPERIMENTAL RESULTS AND DISCUSSION

Typical fringe patterns representing the distribution of isothermal lines in the enclosure are shown in Figures 3 and 4. One of the common features observed in all photographs is the thermal plume in the upward direction, just above the heat source, with very dense fringe gaps around it. Based on the deflection direction of temperature fringes observed in the opening, it is found that warm air from the inside flows out through the upper part of the opening, and cold air from the surroundings flows into the enclosure through the lower part of the opening. To satisfy mass conservation considerations, the mass flow rate of inflow must be the same as that of the outflow.

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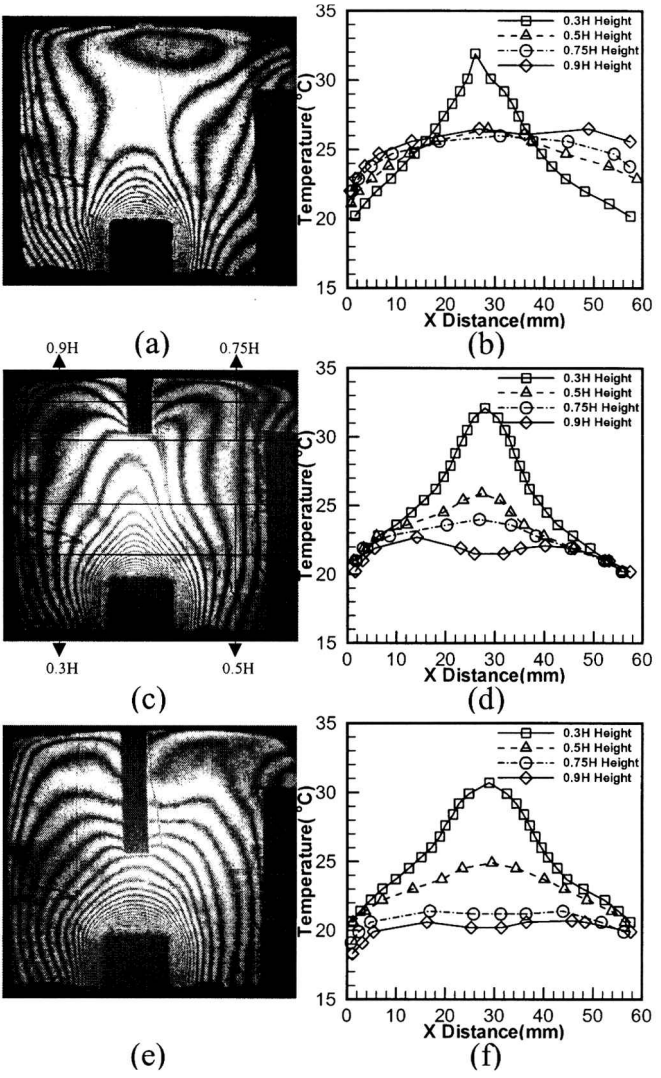

Figure 3. Photographs of fringes and the horizontal temperature distribution with $H_o = 0.22H$, $T_h = 40^{\circ}$C: (*a,b*) no divider; (*c,d*) $H_d = 0.22H$; (*e,f*) $H_d = 0.46H$.

Photographs of fringes and the horizontal temperature distribution along several heights with $H_o = 0.22H$, $T_h = 40^{\circ}$C, are shown in Figure 3. For this small opening length, the mass flow rates of air inflow and outflow through the opening are not high. Therefore, a temperature field is developed which seems independent of the opening in the right wall, and which results in an almost symmetrical temperature distribution within the enclosure. The existence of a divider in the center of top surface prevents the development of an upward flow from the heat source. Accordingly, the temperature

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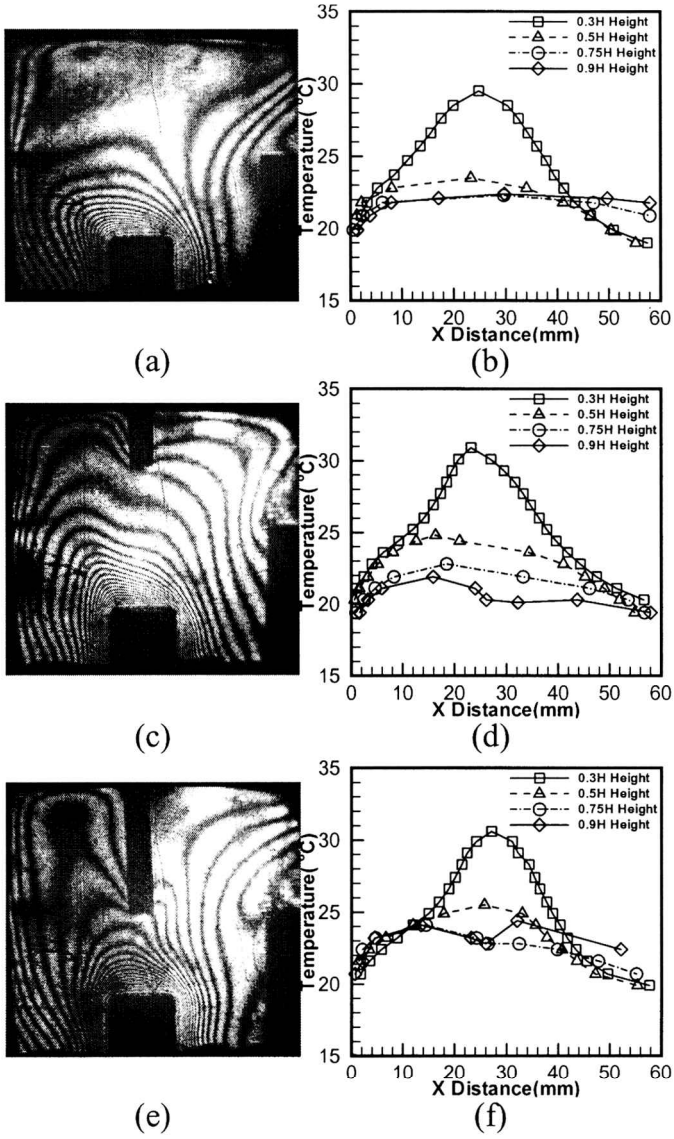

Figure 4. Photographs of fringes and the horizontal temperature distribution with $H_o = 0.46H$, $T_h = 40^{\circ}$C: (*a*,*b*) no divider; (*c*,*d*) $H_d = 0.22H$; (*e*,*f*) $H_d = 0.46H$.

in the upper region with the longest divider is the lowest among the three cases of divider length. Without the divider (Figures 3*a*, 3*b*), the upward flow and the resulting circulation are well developed, which causes an increase in the temperature of the top center of the enclosure. Therefore, there exists a very wide region of uniform temperature at the top center of the enclosure. In Figure 3*b*, the temperatures of the top center of the enclosure, namely, from $y = 0.5H$, are almost uniform. Due to the high circulation rate,

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the temperatures in the left and right regions are lower at lower enclosure heights and become higher as the enclosure height increases.

When a divider of length $0.22H$ is attached to the enclosure's top, as shown in Figures 3*c* and 3*d*, it obstructs the upward flow and reduces the strength of circulation. The temperatures in the left and right regions do not show any big differences due to the reduced circulation, and the uniform temperature region at the center of the enclosure ceases to exist. In the case of the longest divider length, $H_d = 0.46H$ (Figures 3*e* and 3*f*), the divider hinders the upward flow significantly and separates the flow into two streams, on either side of the divider, which results in a weaker circulation and the lowest flow rates through the opening among the three cases of small opening length examined. Due to this weakened circulation, the temperatures in the left and right regions are higher at the lower height and become lower at the higher level, which is the opposite of that found when the divider is absent.

Figure 4 shows photographs of fringes and the horizontal temperature distribution along several heights with $H_o = 0.46H$, $T_h = 40^{\circ}\mathrm{C}$. The mass flow rates of inflow and outflow air through the opening are now increased. Therefore, the upward flow from the heater is forced to move into the left region of the enclosure. Without the divider the upward flow develops well and is similar to that found for the small opening, showing a very wide uniform temperature region at the left and top center of the enclosure. However, the mass flow rate of inflow is maximal and the tendency of the upward flow into the left region is strongest.

When the divider length is $0.22H$, the inclination of the upward flow becomes weaker due to a decrease in the inflow mass flow rate caused by the divider. No wide uniform temperature region is observed in the left top region as the hot upward air flow is weakened and separated into two streams of similar flow rate. When $H_d = 0.46H$, the longest divider almost splits the enclosure into left and right regions. In the left region there appears a wide region of uniform temperature. This is caused by the establishment of an upward air flow resulting in good heat transfer from the heat source to the top region. Most of the upward flow from the heat source goes to the left region because the cold inflow pushes the upward flow into this left-hand-side region, which leads to the smallest inflow and outflow mass flow rates.

The effect of divider height on the horizontal temperature distribution at several heights with $H_o = 0.22H$, $T_h = 40^{\circ}\mathrm{C}$, is shown in Figure 5. The divider does not affect the horizontal temperature distribution appreciably at $y = 0.3H$. The effect starts to appear at $y = 0.5H$. As explained previously, the divider hinders the development of hot upward flow into the top region such that the temperature without the divider is generally higher than that obtained with the longest divider length ($H_d = 0.46H$). This difference becomes greater as the height increases. Exception to this general tendency is found in the right region at $y = 0.5H$ due to the effect of cold inflow at this height, but this effect is reduced as the height is increased further.

Figure 6 shows the effect of the divider height on the horizontal temperature distribution at several heights with $H_o = 0.46H$, $T_h = 40^{\circ}\mathrm{C}$. Compared with the cases involving small opening length, the effect of the divider length is not significant, due to the increased flow rates through the larger opening. Therefore, the temperature inside the enclosure depends on both the flow rates through the opening and how well the effect of the cold air flow is blocked by the divider. In Figure 5, for a small opening length, higher temperatures occurs when there is no divider. On the other hand, for a

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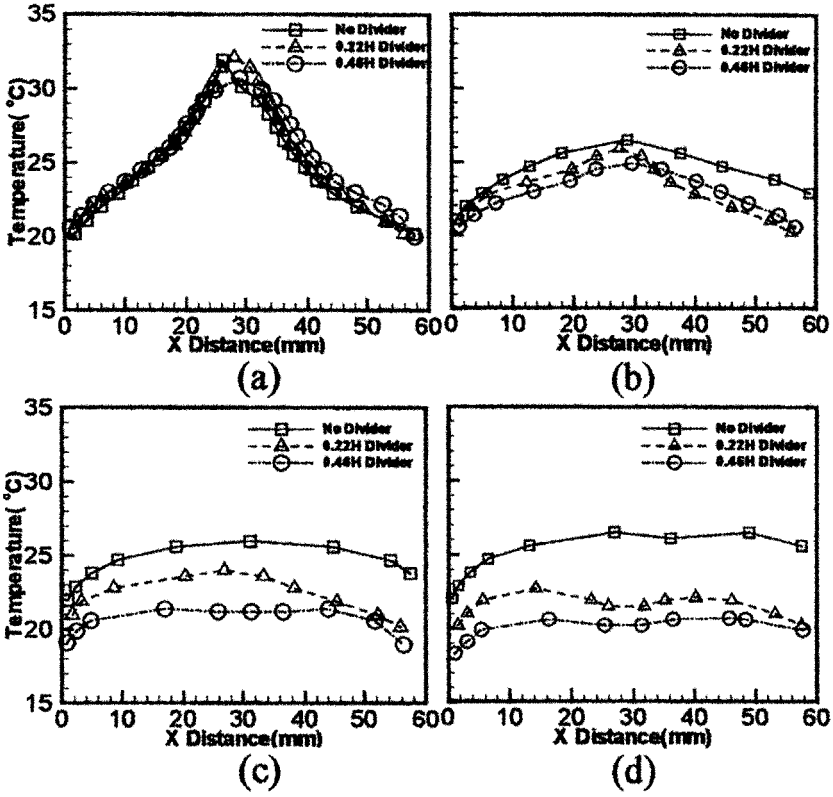

Figure 5. Effect of the divider length on the horizontal temperature distribution with $H_o = 0.22H$, $T_h = 40^\circ$C: (*a*) $y = 0.3H$; (*b*) $y = 0.5H$; (*c*) $y = 0.75H$; (*d*) $y = 0.9H$.

large opening length the temperatures for the longest divider are a little higher than those for other cases. These higher temperatures result from the lower cold air flow rates and the blockage of this cold inflow by the longest divider. In particular, in the left region at $y = 0.75H$ and $0.9H$, the cold inflow moves the upward flow of hot air into the left region and this hot circulatory flow is trapped by the long divider, which results in a higher temperature.

Figure 7 shows the effect of opening length on the horizontal temperature distribution along $y = 0.3H$ and $0.75H$ with $T_h = 40^\circ$C. At lower height in the left region, when $H_d = 0$ and $0.22H$, a large opening with an associated increased flow rate moves the hot upward flow into the left region, resulting in a shift in the maximum temperature to the left, which is a little higher for the large opening length than for the small opening length. However, when $H_d = 0.46H$, the long divider weakens the effect of the increased cold flow, and results in the same temperature for both small and large opening lengths. At the same height in the right region, without a divider, a lower temperature for the large opening is caused by increased cold air inflow. The effect of this increased cold flow is reduced for $H_d = 0.22H$, due to the existence of the divider. When $H_d = 0.46H$, the temperature for the larger opening is once again lower than that for a small opening, because the increased cold inflow is trapped in the right region by the longest divider.

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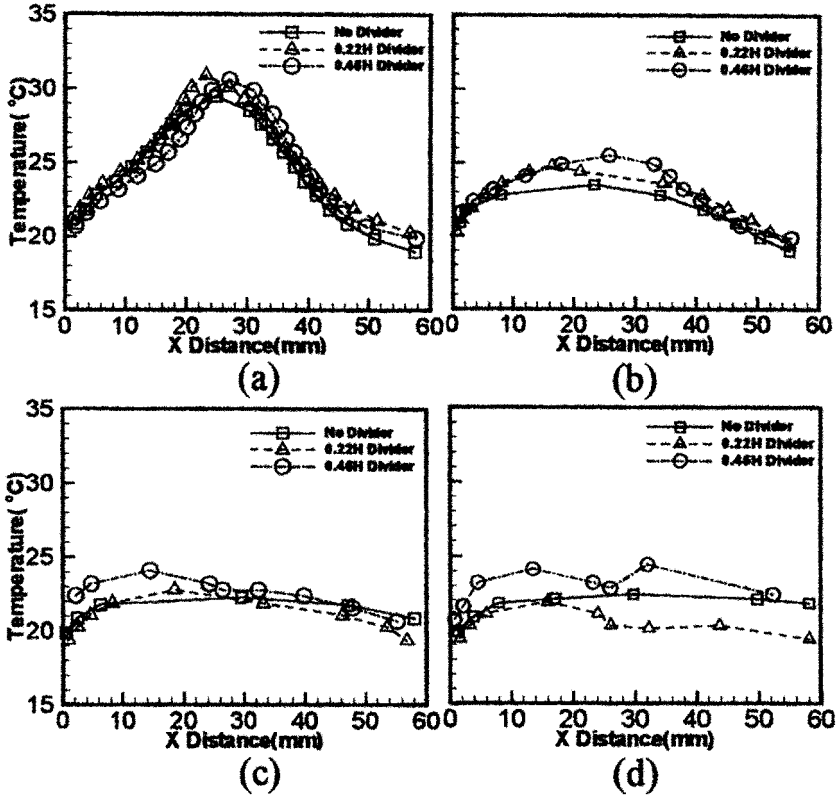

Figure 6. Effect of the divider length on the horizontal temperature distribution with $H_o = 0.46H$, $T_h = 40^{\circ}$C: (*a*) $y = 0.3H$; (*b*) $y = 0.5H$; (*c*) $y = 0.75H$; (*d*) $y = 0.9H$.

At $y = 0.75H$, without the divider, the temperature for the large opening length is much lower than that for the small opening length because hot air inside an enclosure is mixed well with the cold inflow due to the increased flow rate through the larger opening length. When $H_d = 0.22H$, the upward flow is hindered by the existence of a divider, such that the temperature in the case of the small opening length becomes lower than that when no divider is fitted. The opposite situation applies in the case of the longest divider. The higher temperature found in the left region for a large opening is caused by the well-developed upward air flow resulting from pushing generated by the increased inflow.

The vertical temperature distribution at the opening with $T_h = 40^{\circ}$C is shown in Figure 8 for $H_o = 0.46H$. As shown qualitatively in Figure 4, the warm air inside flows out through the upper part of the opening and cold air from the surroundings flows into the enclosure through the lower part of the opening. Without a divider the temperature of outflow is the highest among the three cases as the upward and outward flow is not hindered by a divider. However, when $H_d = 0.22H$, the presence of the divider hinders the development of upward flow from the heat source, resulting in a decrease of outflow temperature. The temperature distribution for $H_d = 0.46H$ is very different

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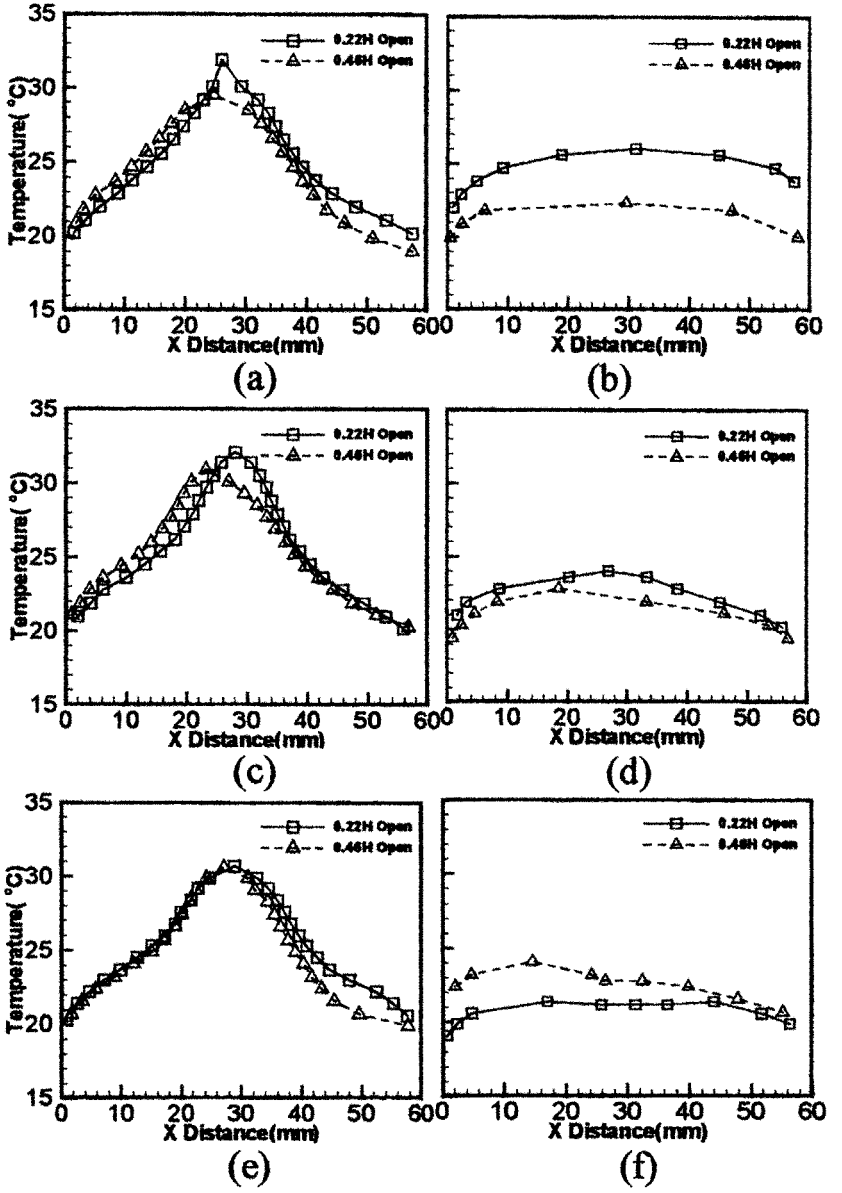

Figure 7. Effect of the opening length on the horizontal temperature distribution with $T_h = 40^{\circ}$C: (*a*) $y = 0.3H$, no divider; (*b*) $y = 0.75H$, no divider; (*c*) $y = 0.3H$, $H_d = 0.22H$; (*d*) $y = 0.75H$, $H_d = 0.22H$; (*e*) $y = 0.3H$, $H_d = 0.46H$; (*f*) $y = 0.75H$, $H_d = 0.46H$.

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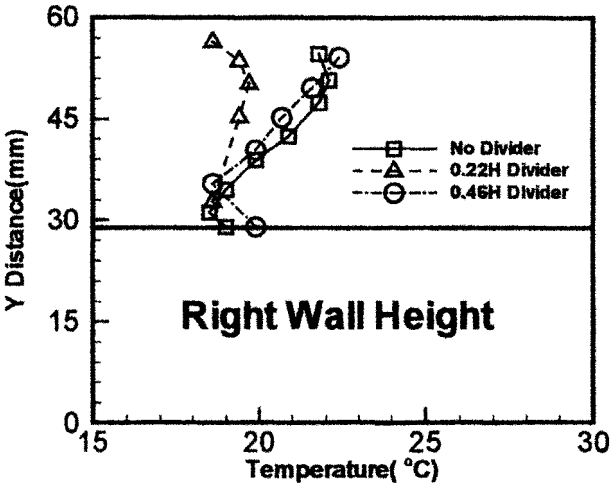

Figure 8. Temperature distribution at the opening with $T_h = 40^{\circ}$C.

when compared with other cases. The maximum outflow temperature is located below the top surface when $H_d = 0$ and $0.22H$. When $H_d = 0.46H$, high-temperature liquid flows only along the top surface, with maximum temperature at the surface. With the longest divider the upward flow is completely separated into two streams and the outflow is forced toward the surface by the increased inflow, resulting in a higher temperature at the surface.

Figure 9 shows the effect of heat source temperature change from 30 to 50°C, with $H_o = 0.46H$ and without a divider. The structure of fringe patterns between cases is very similar except that denser fringes are found around the heat source when its temperature is increased. When the heat source temperature increases, the upward flow from the heat source becomes stronger, resulting in an increase in inflow mass flow rate through the opening. Therefore, as the temperature of the heat source increases, the upward flow inclines more to the left region. To investigate the temperature distribution shown in Figure 9 qualitatively, we measured the vertical temperature distribution above the heat source along $x = 0.6W$, as shown in Figure 10. For the case of wide opening length, without a divider, a broad, uniform temperature region is well established in the enclosure's upper center, which is shown in Figure 9. As expected, the temperature drops rapidly just above the heat source and reaches a uniform center region temperature about 10 mm above the heat source.

CONCLUSIONS

In this study, natural convection in an enclosure with an opening in the right vertical wall and a heat source on the bottom surface was investigated using a holographic interferometric technique. The effects of the opening length, the height of a divider attached to the top surface, and heater temperature on the temperature distribution within the enclosure were examined. Warm air inside flowed out through the upper part of the opening and cold air from the surroundings flowed into the enclosure through the

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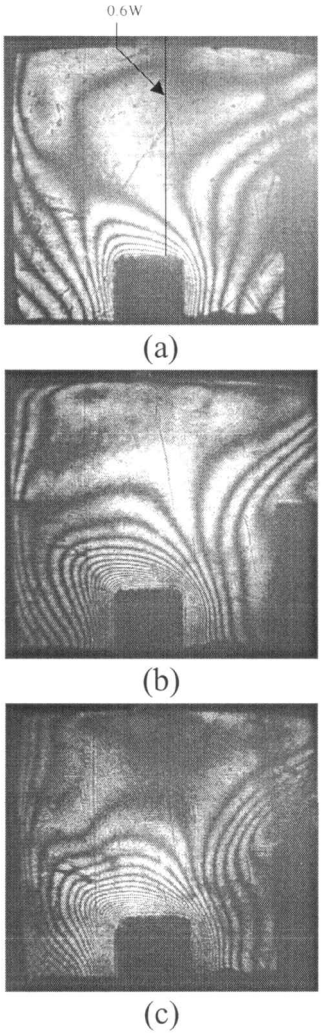

Figure 9. Photographs of isothermal fringes showing the effect of heater temperature: (*a*) $T_h = 30^\circ$C; (*b*) $T_h = 40^\circ$C; (*c*) $T_h = 50^\circ$C.

lower part of the opening. The flow rates of the inflowing and outflowing air through this opening increased with larger opening length, smaller divider height, and higher heater temperature. In the case of the small opening length, the opening size did not significantly affect the upward warm air flow, and resulted in a symmetrical temperature distribution. The divider prevented the development of upward hot air flow onto the top of the enclosure such that the temperature without the divider was generally higher than that achieved with the longest divider. In the case of the large opening length, the upward flow from the heater was forced to move into the left-hand side of the enclosure by the increased cold inflow. The effect of the divider height was not significant, due to the increased flow rates through the increased opening size. The temperatures in the case of the longest divider were a little higher than those for the other cases, due to the reduced flow of cold air and the blockage of the cold air inflow caused by the longest divider.

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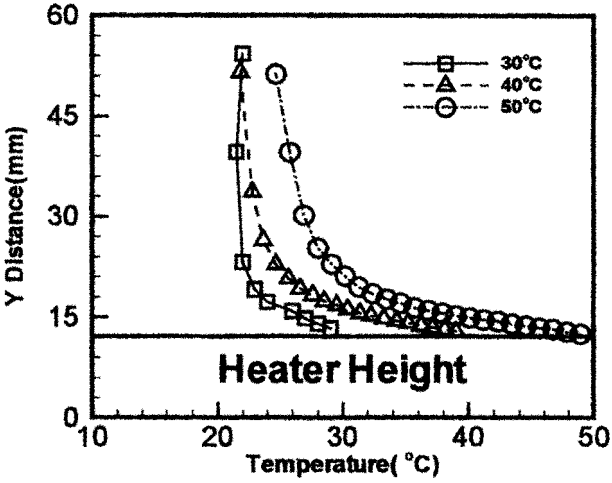

Figure 10. Effect of heater temperature on the vertical temperature distribution along $x = 0.6W$.

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