垂直圓柱容器中低速空氣噴流衝擊至加熱圓盤之混合對流渦流結構實驗研究

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摘要

在此論文中，利用實驗流場觀測及溫度量測，探討在垂直絕熱圓柱中一低速空氣噴流撞擊至加熱圓盤時，穩態與非穩態之對流渦流結構特性。其中，爐體內的渦流型態係利用幻燈機所產生之垂直與平行的光頁進行流場觀測。特別的是空氣進入爐體的流量是從 0.2 到 9.3 slpm (Standard liter per minute)，若以兩個管徑（分別是 10.0 與 22.1mm）來說雷諾數分佈是從 12 到 1,258，而入口空氣與加熱圓盤之間的溫差則是從 0 到 25℃，所以在不同的高度下（10、15、20 及 30 mm）雷利數則是從 0 到 63,420。

實驗結果顯示爐體內典型穩定的渦流包含有兩個 Inertia-driven rolls 與一個 buoyancy-driven roll，Inertia-driven rolls 主要是受到雷諾數的影響，若雷諾數增加則此渦流會變大且增強，不過 Primary inertia-driven roll 也會受到溫差的影響。Buoyancy-driven roll 主要受到雷利數的支配，尤其是爐體內的頂板到底板的距離增加則此 roll 會變大，在最高的高度（30.0 mm）中 Primary inertia-driven roll 與 Buoyancy-driven roll 兩個都會變大而且相互的碰觸在一起，結果使得兩個 roll 之間沒有空間可讓 Secondary inertia-driven roll 生成。除此之外，我們也發現如果降低頂板到底板距離，除了 30.0 到 20.0 mm 以外，會使得 Inertia-driven roll 出現的

臨界雷諾數延遲，高度降低後同時也降低了雷利數，所以 Buoyancy-driven roll 的尺寸與強度都減小。另外，在比較高的雷諾數時，有三次渦流 Secondary inertia-driven roll 在頂板且靠近衝擊流附近產生，而且如果繼續增加雷諾數並且超過三次流出現時的臨界雷諾數，爐體內的渦流會開始不穩定，也就是渦流的變化與時間有關連且從穩定漸漸趨向於不穩定，很顯然的這是因為衝擊流的慣性力造成的不穩定，而且這個渦流不穩定臨界雷諾數會因為雷利數增加而延遲。

對於比較大的管徑 22.1 mm 其 Inertia-driven rolls 在相同的流量及溫差下的尺寸與強度都比小管徑 10.0 mm 還要小且弱，不過 Buoyancy-driven roll 卻不受管徑的影響。對於雷利數為零時且入口管徑為 10.0 mm 時，Secondary inertia-driven roll 出現的臨界雷諾數大約為 180，大管徑則約為 220。同時我們也發現 Buoyancy-driven roll 開始出現時的局部浮慣比約為 33.0。量測穩定或是統計學上穩定的流場在徑向方向的溫度發現有一最大值，這是因為 Primary inertia-driven roll 與 Buoyancy-driven roll 同時存在的關係。

在比較低的浮慣比時，渦流都是穩定且軸對稱的，但是在較高的浮慣比渦流開始變成不穩定，此外較高的浮慣比時，會有新的渦流從加熱底板表面冒出及從 Primary inertia-driven roll 分裂出來，且量測此渦流的溫度場發現只有某些區域受到新的渦流的影響會有震盪的情形，其他的地方渦流則是穩定的。

實驗結果發現 Inertia-driven roll 形成過程，係在噴流衝擊在圓盤上後在噴流周圍會有小的環形渦流產生，然後 Inertia-driven roll 迅速的成長直到穩定。在較高的雷諾數會有另外一個 roll 生成，且此 roll 也會成長，這也就是我們已知的 Primary 與 Secondary inertia-driven roll，在較高的雷諾數時 roll 從形成到穩定的時間比較短。

最後，我們也發表了不穩定渦流的週期頻率與渦流尺寸及位置的經驗公式，進一步提供 Buoyancy-driven roll 開始出現的臨界條件，另外根據實驗結果，特別以流譜圖描述渦流在高度為 20.0 mm 時的空間狀態。

Experimental Study of Mixed Convective Vortex Flow Structure in a Low Speed Air Jet Impinging onto a Heated Disk in a Vertical Cylindrical Chamber

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ABSTRACT

Experimental flow visualization and temperature measurement have been conducted in the present study to investigate the steady and time dependent characteristics of the mixed convective vortex flow resulting from a low speed air jet impinging onto a heated horizontal circular disk confined in a vertical adiabatic cylindrical chamber. The vortex flow patterns in the chamber are illuminated by the vertical and horizontal plane light sheets produced by passing parallel lights from an overhead projector through adjustable knife edges. Specifically, in the present experiments the air flow rate is varied from 0.2 to 9.3 slpm (standard liter per minute) for the jet Reynolds number ranging from 12 to 1,258 with two different injection pipes (diameter 10.0 and 22.1 mm) and the temperature difference between the disk and the air injected into the chamber is varied from 0 to 25.0℃ for the Rayleigh number ranging from 0 to 62,430 at the jet-to-disk separation distance of 10.0, 15.0, 20.0 and 30.0 mm.

The experimental results show that typically the steady vortex flow in the processing chamber consists of two inertia-driven and one buoyancy-driven circular

rolls. The inertia-driven rolls are mainly affected by the jet Reynolds number. They are larger and stronger at a higher Re_j. But the primary inertia-driven roll is also affected to a certain extent by the disk-to-jet temperature difference. The buoyancy-driven roll is dominated by the Rayleigh number. The rolls in the processing chamber are larger for a longer jet-to-disk separation distance. At the largest H (=30.0 mm) tested here both the primary inertia-driven roll and buoyancy-driven roll are relatively large and they can contact with each other. Hence no space is available for the second inertia-driven roll to appear. Besides, we also note that a reduction in the jet-to-disk separation distance causes a delayed onset of the inertia-driven rolls except for H reduced from 30.0 to 20.0 mm and in the meantime causes a substantial decrease in the Rayleigh number since $Ra \propto H^3$, which in turn significantly reduces the size and strength of the buoyancy-driven roll. In the upper range of the jet Reynolds number tested here a small tertiary inertia-driven circular vortex roll appears near the upper wall of the chamber around the impinging jet. As we continue to increase the jet Reynolds number slightly beyond the critical Re_j for the onset of the tertiary roll, the flow in the processing chamber does not reach any steady state at long time. Instead, the flow becomes time dependent and experiences a transition from steady to unsteady states. Obviously, this transition is driven by the jet inertia. Moreover, the critical Re_j for this steady-unsteady transition increases with Ra at given H.

For the larger injection pipe with D_j=22.1 mm, the inertia-driven rolls are smaller and weaker at the same jet flowrate and temperature difference between the disk and jet. However, the buoyancy-driven roll is only slightly affected by the injection pipe diameter. For Ra=0, the onset of the secondary inertia-driven roll occurs at $Re_j \approx 180$ for the small injection pipe. While for the large injection pipe the onset of the secondary roll takes place at $Re_j \approx 220$. Our data also suggest that the critical Re_j for onset of the buoyancy-driven roll takes place when the local buoyancy-to-inertia ratio at the edge of the disk $Gr/Re_{we}^2 \approx 33.0$ within the experimental uncertainty. The measured radial temperature distributions at steady and statistically stable state in the flow possess a peak, which in turn results from the presence of the counter-rotating primary inertia-driven and buoyancy-driven rolls.

At low buoyancy-to-inertia ratios the vortex rolls are steady state and axisymmetric. But the vortex flow becomes time dependent flow at high buoyancy-to-inertia ratios. Besides, at high buoyancy-to-inertia ratios new vortex rolls are induced by the additional thermal plume rising from the heated disk and the splitting of the primary inertia-driven roll. The temporal characteristics of the time periodic vortex flows deduced from the time histories of the air temperature indicate that in the region dominated by the new rolls the flow oscillates significantly with time. Elsewhere the flow is steady essentially.

The results from the experiment for the formation of the inertia-driven vortex flow for $\Delta T=0°C$ show that immediately after the jet impinging onto the disk a small circular roll is induced around the jet and the roll then grows quickly to arrive at steady state. At a high Re_j an additional roll is induced at the moment when the existing roll has grown to certain size and strength. These two rolls are known as the primary and secondary inertia-driven rolls. It is also noted that at a higher Re_j the period of time for the vortex flow to evolve to the steady state is shorter.

Finally, empirical equations are proposed to correlate the oscillation frequency of the time periodic flow, and the size and location of the vortex rolls. Furthermore, the conditions for the onset of the buoyancy driven rolls are given. Based on the present data, a flow regime map is provided to delineate the temporal state of the vortex flow for H=20.0 mm.