LDA: An Experimental Whole Field Investigation on Confined Rotating Flow with and without Vortex Breakdown

by

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ABSTRACT

Rich complicated flow problems present in rotating flow inside cylindrical container, secondary flows, vortex breakdown, to name a few. The experimental research on vortex breakdown in rotating flows has been limited to visualizations up to now, and there are few quantitative measurement results. For the rotating flow with vortex breakdown, there are sharp changes of velocity distribution, especially direction of the fluid motion. Therefore, large number of measurement points is necessary to make clear the flow. With high measurement precision and broad dynamics band, LDA is suitable for whole field investigation on complicated recirculating flow with and without breakdown. However, it is unfortunately a point-by-point method, which makes duration of experimental whole field investigation much long. Constant working condition is necessary and important for whole field measurements for the reason of two factors, or the obvious variation of room temperature during long time measurement and the friction between the rotating boundary and the working fluid. The popular method to keep working condition constant in most experimental apparatuses is to place a high-precision constant temperature water tank outside of the flow field. But it makes the measurement system complicated and the cost is high. For the confined rotating flow inside cylindrical container with a rotating top lid, the method of adjusting the rotating rate dependent on measured temperature to keep Reynolds number is presented here, as a solution to the appreciable viscosity dependence of the working fluid on temperature. It is experimentally testified that the method is convenient to be used, and can keep the flow pattern at the same Reynolds number with high precision for long time. An experimental whole field investigation on confined rotating flow inside cylindrical container via LDA is presented in the paper. For H/R=1.51, Re=330, 520, 610, 790, 990, 1290 and 2180, the whole field velocity distribution in the meridional plane is obtained. The flow patterns with existence and disappearance of vortex breakdown are made clear.
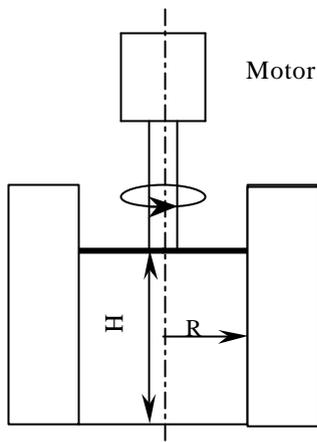
Fig.1. Schematical diagram of experimental apparatus: confined rotating flow inside cylindrical container with a rotating top lid. The rotating rate of the motor is under control of a frequency converter with precision of 0.01Hz.

1. INTRODUCTION

Ever since Escudier (1984) found single, double and triple vortex breakdowns in rotating flow inside confined cylindrical container with a rotating lid, cylindrical container has been widely employed as the experimental apparatus. There is no inflow and outflow, and the boundary condition can be controlled with high precision. However, in spite of thoroughly experimental and numerical work, the fundament of vortex breakdown has not been generally acknowledged up to now, and stability criteria are still missing. Most of those experimental investigations are based on visualizations (e.g. Escudier 1984, 1988; Fujimura et al., 1996, 1997), few quantitative data are experimentally obtained. To gain insight into mechanism of vortex breakdown, the quantitatively experimental investigation is still in development.

For complicated recirculating flow with vortex breakdown, there are sharp velocity changes in the whole field, especially direction of the moving fluid. Therefore, large number of measurement points is necessary to make clear the flow structure, especially the vortex breakdown region. As a noninvasive and matured technique, LDA is a good way to further the experimental work. Unfortunately, it is not a whole field but a point-by-point measurement method, although with high precision and broad dynamics band. Therefore, the overall duration of whole field measurement is too long, and it brings difficulty in keeping the flow at the same working condition.

The main work of the paper is an experimental whole field investigation on confined rotating flow with and without vortex breakdown via LDA. Firstly, the method to keep constant Reynolds number for long time is introduced, as a solution to the appreciable viscosity dependence of the working fluid on temperature. For H/R=1.51, Re=330, 520, 610, 790, 990, 1290 and 2180, the whole field velocity distribution in the meridional plane is experimentally detected. Then the flow patterns at pre-breakdown, with existence and disappearance of breakdown at high Reynolds number are made clear.

2. CONSTANT REYNOLDS NUMBER METHOD

For the experimental investigation on vortex breakdown inside confined cylindrical container with a rotating lid, glycerin-water mixture (e.g. Fujimura et al., 1996, 1997) or silicone oil (e.g. Liu et al., 2000) is usually chosen as the working fluid. Its dependence of kinematic viscosity on temperature is appreciable, which is 5% and 2% respectively. During long time experiment, if without special measurements, the temperature of the working fluid varies much for the reason of considerable variation of room temperature and the friction between the rotating boundary and the working fluid. The common solution is to place a rectangular water tank with heater and stirrer inside, to make temperature of the working fluid constant with high precision by circulation. However, the experimental apparatus is complicated and the cost is high.
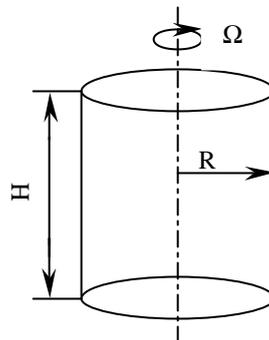
Fig.2 Rotating flow confined inside cylindrical container

An indirect method of keeping constant Reynolds number without constant temperature water bath is introduced here. First of all, it is assumed that the temperature of the working fluid is constant in the whole flow field, for the reason of the forced circulation by the rotating lid. The rotating flow as shown in Fig.2 is dependent on two characteristic non-dimensional parameters, or the aspect ratio Ar=H/R and

Reynolds number Re=$\Omega R^2 / \boldsymbol{n}$, in which H and R are height and radius of the container respectively, Ω is the angular velocity of the rotating top lid and $\boldsymbol{n}$ is kinematic viscosity of the working fluid.

The main procedure of the method is to adjust the rotating rate dependent on the temperature variation, to keep Re constant within allowable errors. Obviously, the whole field shall be separated into several blocks in advance, then the measurements can be done block by block. The rotating rate of the top lid during measurement in each block is defined as

$$n(T_1) = \frac{\boldsymbol{n}(T_1)}{\boldsymbol{n}_s} n_s \tag{1}$$

$$\mathrm{Re}_s = \frac{\boldsymbol{p} n_s R^2}{30 \boldsymbol{n}_s} \tag{2}$$

in which n_s and $\boldsymbol{n}_s$ is chosen as the standard rotating rate and kinematic viscosity to define the Reynolds number, T_1 is the predicted temperature during measurement of the next block. So after measuring one block, the change of rotating rate can be calculated from the predicted temperature. For each block, the measurement results shall be converted to the one at standard condition

$$\vec{u}_s = \frac{n_s}{n(T_1)} \vec{u}(T_1) \tag{3}$$

The precision of this method depends on variation of temperature during measurement in each block and the predicted temperature, which is known from trial-and-error method. Of course, the fewer points grouped into one block, the easier the prediction of temperature and the less its variation. Therefore, the preconditioned variation of temperature in each block is a compromise among the precision of constant Reynolds number, the number of measured points and the overall duration of experiment. If variation of temperature is higher than the preconditioned one or the predicted temperature is out of its variation, it is convenient to change the rotating rate and measure it again.

The experimental system error of constant Reynolds number is defined as

$$\boldsymbol{e}_{\mathrm{Re}} = \frac{|\Delta \mathrm{Re}|_{\max}}{\mathrm{Re}_s} \tag{4}$$

in which $|\Delta \mathrm{Re}|_{\max}$ is the maximum deviation of Reynolds number from the one at standard condition.

The aforementioned method is validated experimentally by measurement results of the axial velocity profile at the axis, which is at different temperature region but the Reynolds number is kept constant. For H/R=1.51, Re=1500 and 1700, the profile of the axial velocity component at the axis is shown in Fig.3, in which the axial velocity component u and the axial coordination location are nondimensionalized as $u' = u/\Omega R$ and $z' = z/H$. The measurement parameters for different cases are listed in Tab.1, in which z_1' and z_2' are the location of upstream and downstream stagnation points respectively. From both Fig.3 and Tab.1, it is obvious that the axial velocity distribution at the axis and location of vortex breakdown changes little although the temperature of the working fluid varies as those three cases.
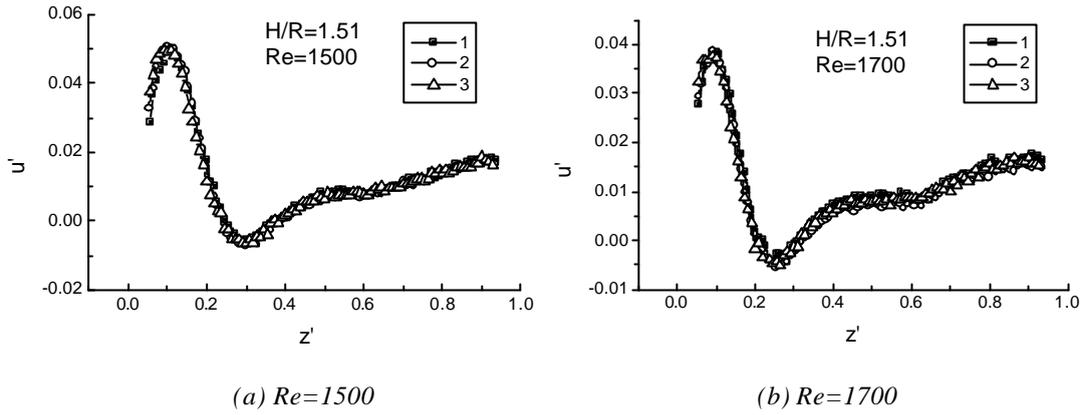
(a) Re=1500   *(b) Re=1700*

Fig. 3. Distribution of the axial velocity component at the axis for three different temperature variation cases (H/R=1.51, Re=1500 and 1700)

Tab.1 Measurement parameters at different temperature variation region for H/R=1500 and 1700

Standard Re	1500			1700		
	1	2	3	1	2	3
T(°C)	19.2~19.4	17.6~17.6	18.4~18.4	19.4~19.6	17.6~17.8	18.4~18.6
n(rpm)	286	295	290	322	334	328
Re	1503~1509	1498~1498	1498~1498	1698~1706	1696~1702	1695~1701
? Re%	0.6	0.13	0.13	0.35	0.24	0.29
z_1'	0.2455	0.2455	0.2409	0.2082	0.2045	0.2091
z_2'	0.3818	0.3864	0.3864	0.3136	0.3227	0.3136

3.   RESULTS AND ANALYSIS

The experimental apparatus shown in Fig.4 is a closed cylindrical container with a rotating top lid. Both sidewall and the bottom lid are at rest. A rectangular tank is placed outside of the cylindrical container. To reduce the curvature effect of glass sidewall, the working fluid, or silicone oil, is filled in both the container and the tank. The rotating rate of the motor is controlled by a frequency converter,
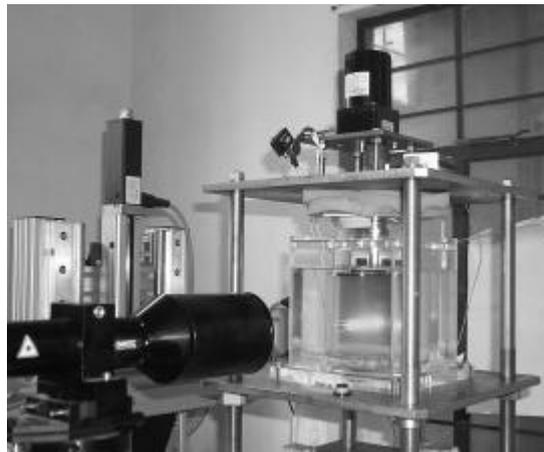
Fig.4 Photograph of experimental apparatus

which makes the experimental apparatus encompass a broad range of Re. The output power precision of the converter is 0.01Hz. Diameter of the rotating lid and inner diameter of the cylindrical container

is 145.00±0.01mm and 146.34±0.02mm respectively. Magnesium oxide is chosen as tracking particles.

The measurement instrument is a 3D DualPDA (Dantec) system. The precision of the traverse system is 1mm/320pulses. Back-scattering mode (green: 514.5nm, blue: 488nm) is used to measure the whole 2-D field in the meridional plane. The maximum deviation of measurement point from the meridional plane is 0.6mm.

For H/R=1.51, the whole meridional flow field at Re=330, 520, 610, 790, 990, 1290 and 2180 is experimentally detected with large quantity of measurement points. The velocity vector maps (left) and streamline diagrams (right) in the meridional plane are shown in Fig.5. The Reynolds number is broad to include the simple rotating flow (a, b, c, d), pre-breakdown flow pattern (e), existence (f) and disappearance (g) of vortex breakdown. With the consideration into obvious change of the fluid motion near the centerline, the measurement grid density in the left region of the vertical straight line as shown in Fig.5 is higher than that in the right part. The dimension parameters are non-dimensionalized as $z' = z/H$, $r' = r/R$.

It is obvious that the internal flow (a) is type of large-scale vortex due to pump suction of the rotating upper lid. With the increase of Re, although the suction effect is enhanced, the vortex center (b, c) keeps at the same location, and the nearby circulation flow changes to be slender to extend effect of the rotating lid to the bottom. When Re=800 (d), a low velocity region at z'=0.7 is formed near the centerline. Most streamlines between the region and the slender vortex begin to change from convex to concave, which tendency makes the fluid to be stagnated at Re=990 (e). It is vortex breakdown as noted in references. With the increase of Re, the size of breakdown region is increased and its location is moved down, together with much low velocity reversed flow inside (f). The breakdown disappears at Re=2180 (g), but the slender vortex near the sidewall is broken down into two isolated vortexes. Therefore, most of the fluid thrown out by the rotating lid is limited to the thin Stewardson boundary flow.

4. SUMMARY

The duration of whole field investigation via LDA is much long. It is difficult to keep experimental system working at the same condition during long time measurement. For LDA investigation of confined rotating flow inside cylindrical container with a rotating top lid, the method of keeping constant Reynolds number by means of changing the rotating rate dependent on temperature of the working fluid is presented here. The method is experimentally testified to be convenient and with high precision.

For H/R=1.51, the whole field velocity distribution in the meridional plane of the cylindrical container is obtained by means of the aforementioned method. The Reynolds number is kept at the same value within high precision. And the flow patterns at pre-breakdown, with existence and disappearance of vortex breakdown are experimentally detected and made clear.

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Escudier, M.P. (1984). "Observations of the Flow Produced in a Cylindrical Container by a rotating endwall," Experiments in Fluids, 2, 189-166

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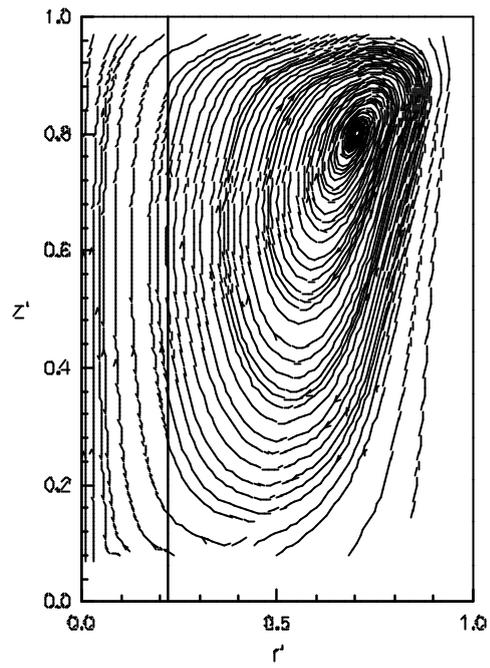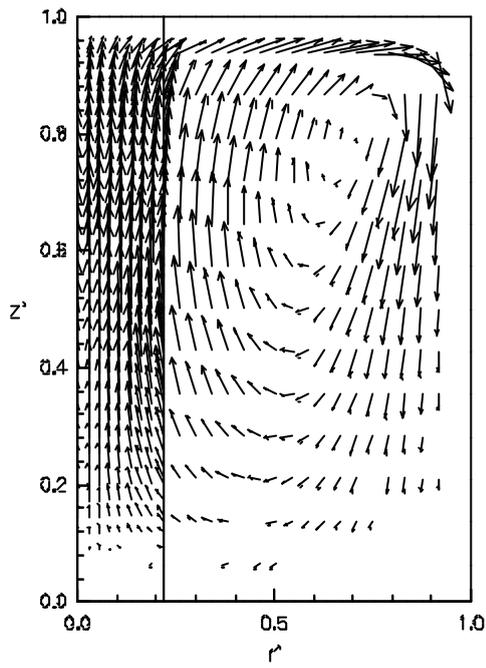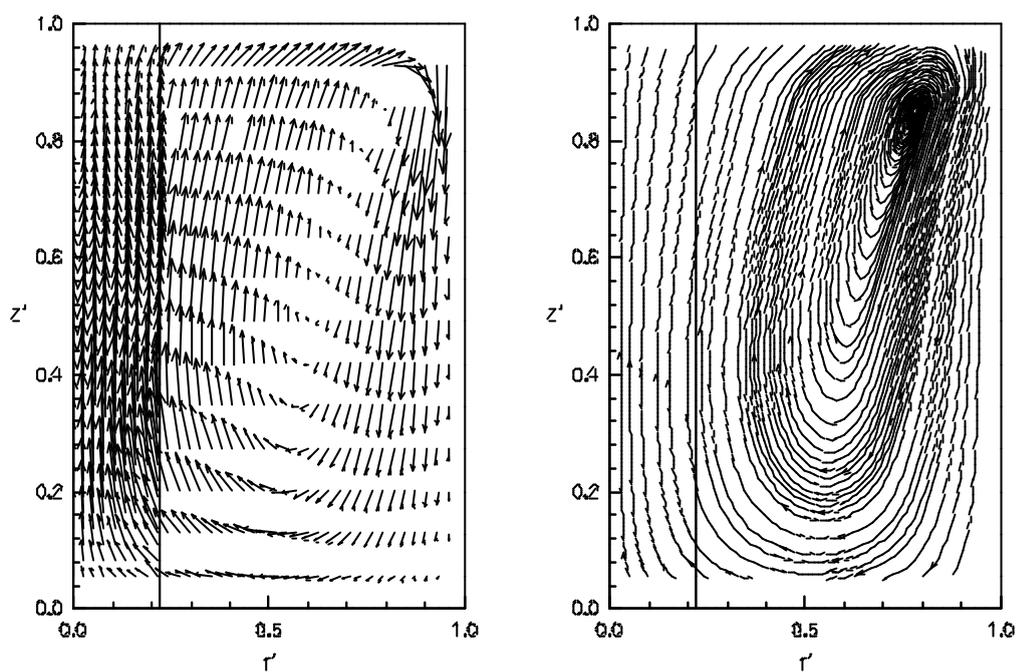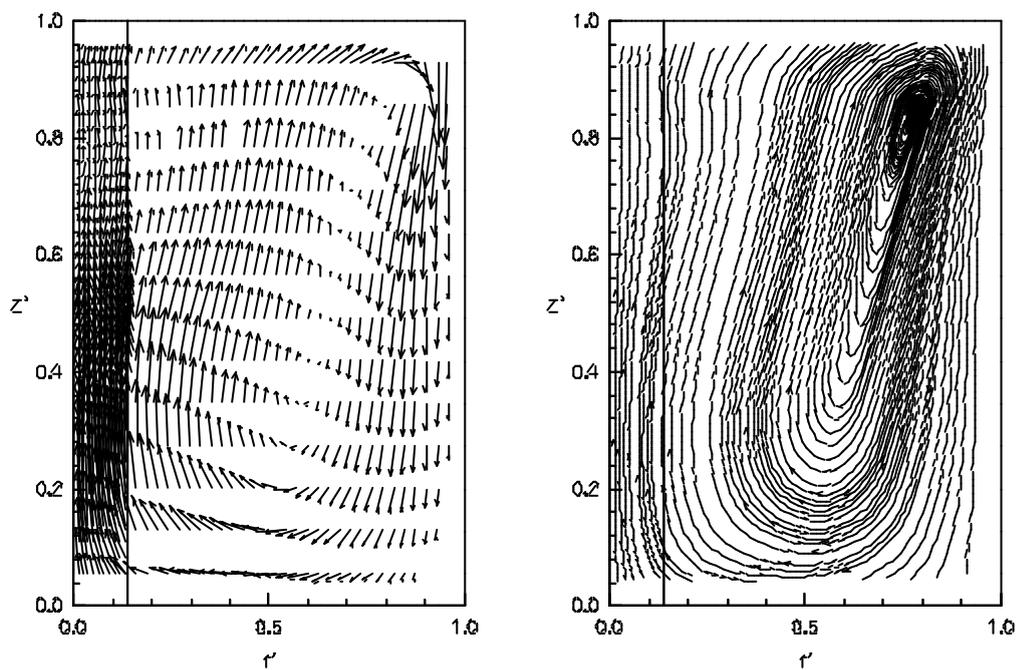
(a)Re=330 (532 measurement points;　e_{Re} =0.3%)
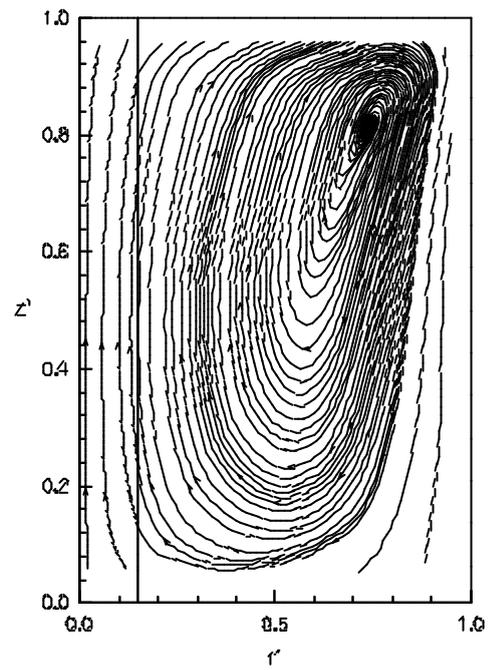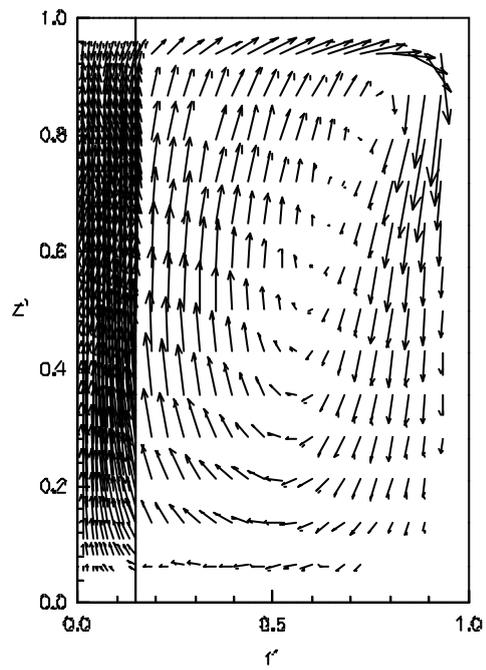
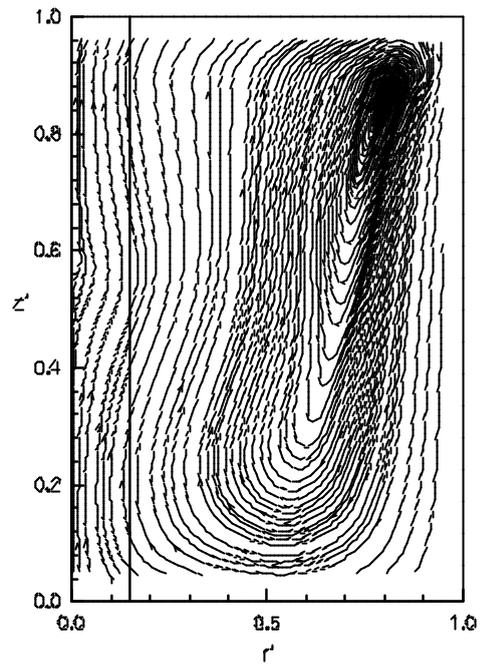*(b) Re=520(658 measurement points;　e_{Re} =1.0%)*

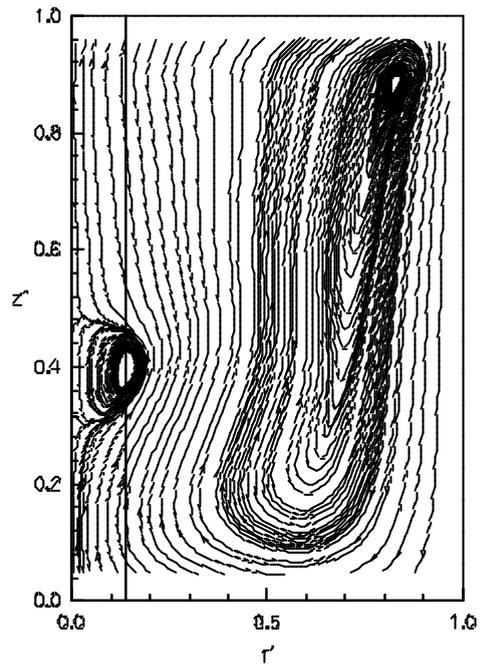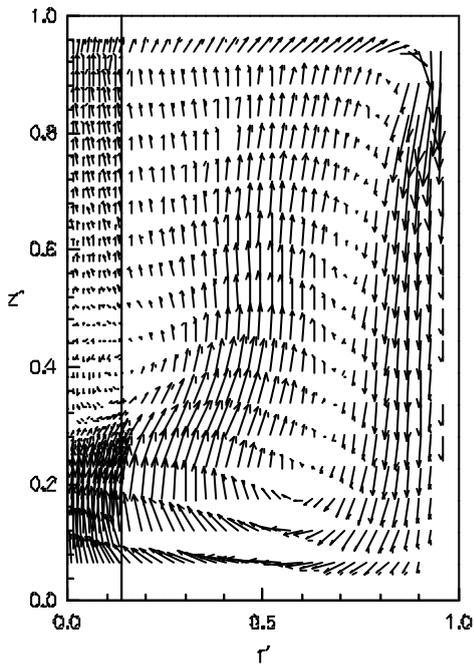*(to be continued)*

(c) Re=610(662 points; e_{Re} =0.6%)

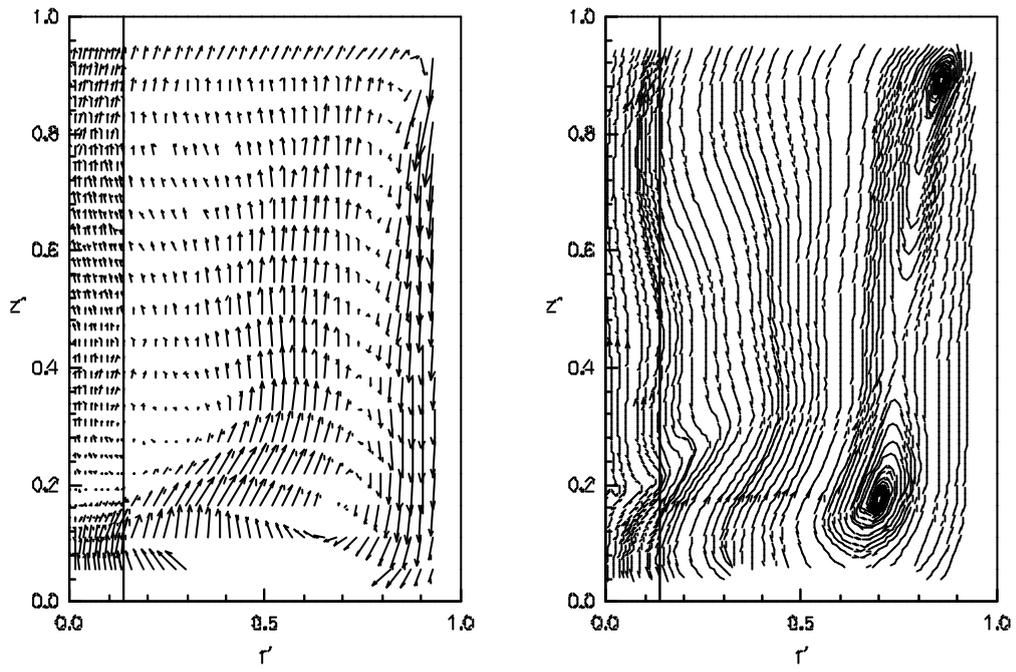*(d) Re=800(768 measurement points; e_{Re} =0.3%)*

(to be continued)
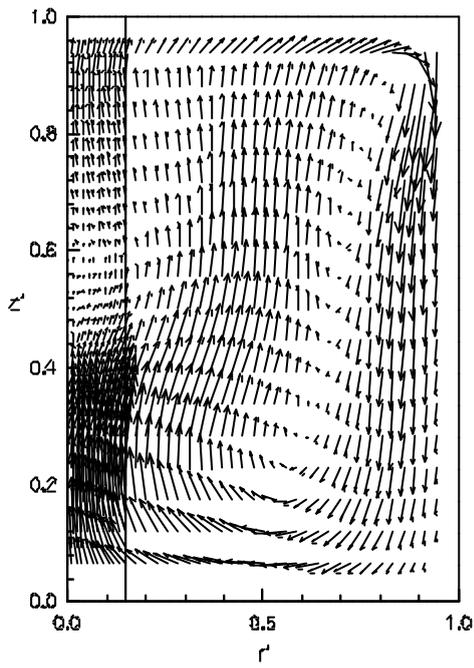
(e) Re=990 (909 measurement points; e_{Re} =0.6%)

(f) Re=1290(891 measurement points; e_{Re} =0.7%)

(to be continued)

(g) Re=2180（872 measurement points； e_{Re} *=0.6%)*

Fig.5. Velocity vector maps (left) and meridional streamline diagrams (right) for H/R=1.51, Re=330,

520, 610, 790, 990, 1290 and 2180