RECIRCULATING FLOW IN A CONFINED SPACE WITH AXISYMMETRIC SUDDEN EXPANSION FOLLOWED BY CONICAL CONTRACTION

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The recirculating flow characteristics in a confined space with axisymmetric sudden expansion followed by a conical contraction section were measured by means of an electrochemical method. Integral scales of space correlation in both longitudinal and circumferential directions were obtained. Also, the recirculating velocity of a large eddy was determined from the measurement of space-time correlation. Experimental results confirmed that there exists a large recirculating eddy near the wall of test chambers.

Introduction

The turbulence characteristics of confined jets with recirculating flow are of particular relevance to the flows in combustion chambers[4], coal gasification furnaces[3] and other chemical reactors. Precise understanding of the nature of recirculating turbulence flow is needed to determine the characteristics of such chemical equipment. However, sufficient knowledge of three-dimensional unsteady turbulent flows with recirculation has not been obtained either theoretically or experimentally. The present authors[6] have reported some flow characteristics in a spray drying chamber. It was suggested that strong recirculating flow could exist when a confined jet without swirl was blown into a drying chamber, and the recirculating flow might affect the drying process of atomized droplets. Thus, we decided to measure both time and length scales of recirculating large eddies in a confined vessel with sudden axisymmetric expansion followed by conical contraction. Most previous investigators[1,2,5] have concentrated their attention on recirculation flows formed by sudden axisymmetric expansion or backward facing step. The recirculating flow observed for the geometry of the present study is much stronger than those observed for simple expansion flow, because the reattchment point is located in the conical section as reported in the previous paper[6]. Thus the experimental results obtained for unsteady and strong recirculating flow may be useful as fundamental data to be compared in the future with more sophisticated turbulence predictions.

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1. Experimental

Three kinds of test sections of the dimensions shown in **Fig. 1** were connected in a water flowing loop. The largest test section, indicated by "L", was geometrically symmetrical to the previously reported spray dryer. The flow developing section (PVC tube of 40 mm inner diameter and 2.4 m long) was connected upstream of the test section. The flow without swirl was suddenly expanded at the entrance of the test section, and 60-degree conical contraction followed at a downstream position. The length of the larger cylindrical part was changed to give other geometries indicated by "M" and "S". Nickel point electrodes (1.0 mm dia.) were flush-mounted on the inside solid wall of test sections. The capital letters A ~ I in Fig. 1 indicate the locations of point electrodes. The detailed location of each point electrode is shown in **Fig. 2**. Twelve point electrodes were flush-mounted in each section, with a 30-degree separation from one another. The inside surface of the sudden expansion section was made of a nickel plate. The mass transfer rate of each point electrode surface was

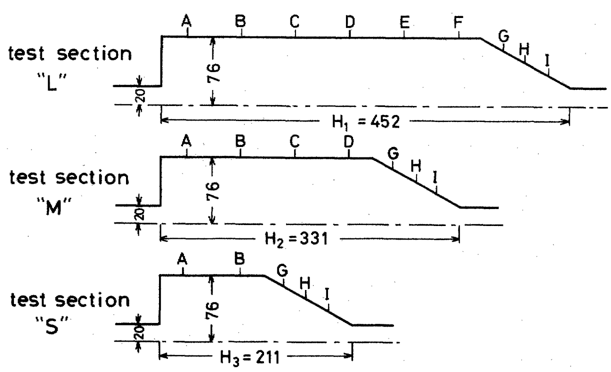

Fig. 1. Dimensions of test sections

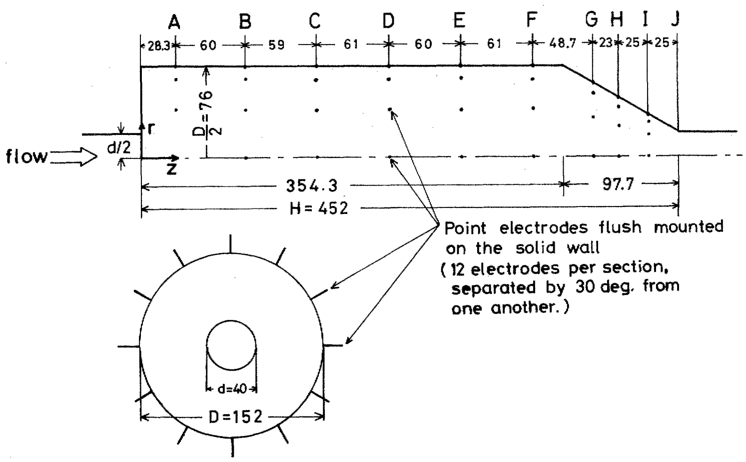

Fig. 2. Detail of "L" type test section

measured by measuring the limiting current of ferricyanide/ferrocyanide redox reaction. The electrolyte had a composition of 0.1 M potassium ferri-ferrocyanide and 1 M sodium hydroxide. Since it was difficult to measure the precise surface area of each electrode inside the test section, the mass transfer coefficient for each point electrode was not calculated from the limiting current data.*[1] Only the fluctuation of limiting current was A-D converted by means of a data logger (Iwatsu Co. Ltd., SY-8504), and the space and time correlations of fluctuating limiting current were calculated by an NEC PC-9801 microcomputer. The sampling frequency of A-D conversion was 50 Hz, and the data size was 15,000 for each electrode.

2. Experimental Results and Discussion

2.1 Scale of recirculating eddy for "L-type" test section

Circumferential space correlations defined by the following equation were measured for the case of $Re = 10^4$, 3×10^4 and 5×10^4, and one of the results is shown in **Fig. 3**.

$$R_\theta = \frac{\overline{i_j \cdot i_k}}{\sqrt{\overline{i_j^2}}\sqrt{\overline{i_k^2}}} \qquad (1)$$

where j and k are the electrode numbers at the same downstream location (i.e. at z=constant.) It is important to notice that large space correlation values are observed even where two point electrodes are separated considerably. Since the value of limiting current is related to the near-wall velocity parallel to the wall, the results shown in Fig. 3 indicate that large recirculating eddies pass near the wall region. It has been certified by previous hot-wire measurements with a split-film probe that the direction of strong

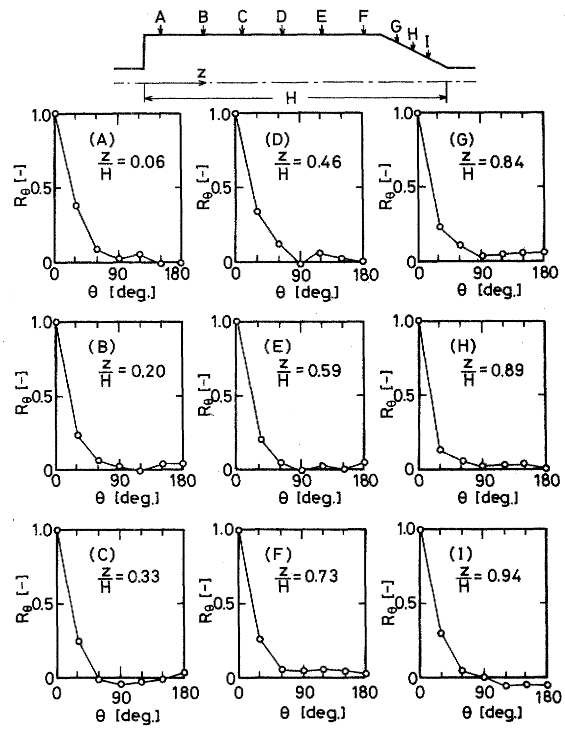

Fig. 3. Circumferential space correlation coefficient measured for "L" type test section at $Re = 5 \times 10^4$

intermittent recirculating flow was upsteam (i.e. from right to left near the wall in Fig. 1).

To estimate the circumferential length scale of recirculating eddies, the integral scale of space correlation, R_θ, was defined as follows:

$$\Lambda_\theta = \int_0^{\theta_1} R_\theta d\theta \qquad (2)$$

where θ_1 is the angle at which the space correlation curve crosses the zero level for the first time. When the space correlation did not have a negative value (e.g. see data at (G); $z/H = 0.844$ in Fig. 3), θ_1 was taken as the angle showing the first minimum value of R_θ

*[1] Because the surface area of point electrodes is very small, the measured value of fluctuating limiting current is propotional to the one-third power of the velocity gradient at the electrode surface.

($\theta_1 = 90$ degree for $z/H = 0.84$ in Fig. 3). The circumferential integral scales thus obtained are plotted in Fig. 4. This diagram includes the three Reynolds number data by the electrochemical method and data of one hot-wire anemometer run. For the hot-wire anemometer experiments, two single hot-wire probes were set near the inside wall of a previously reported spray dryer[6] which has a geometry similar to that of the present experimental apparatus but is around six times the size of the present experimental apparatus. The results shown in **Fig. 4** indicate that the integral scale is almost constant except near both the sudden expansion section and the conical contraction section, where clear recirculating flow may not be observed. The circumferential integral scale has a tendency to decrease according to the increase of inlet Reynolds number. The scale-up data by hot-wire anemometry correspond well to the present electrochemical data.

The longitudinal space correlation of fluctuating limiting currents obtained for two point electrodes aligned in the z-direction was also measured. The longitudinal integral scale was defined as

$$\Lambda_z = \int_{z_1}^{z_2} R_z dz \tag{3}$$

where z_1 and z_2 are the positions where the longitudinal space correlation curve crosses the zero correlation level for the first time and second time, respectively. The experimental results of longitudinal integral scale measurements are shown in **Fig. 5**. This diagram indicates that the integral scale is almost constant except near both the sudden expansion section and the conical contraction section, where clear recirculating flow may not appear. Also it should be noted that the ratio of the integral scale to the length of test section, Λ/H, seems to be independent of inlet Reynolds number.

2.2 Velocity of recirculating eddy

As both longitudinal and circumferential scales of recirculating eddy were determined from the space correlation measurements, it was decided to determine the recirculating velocity of such a large eddy. The space-time correlation defined by the following equation was measured.

$$R_{zt} = \frac{\overline{i_m(t) i_n(t+\Delta t)}}{\sqrt{\overline{i_m^2}}\sqrt{\overline{i_n^2}}} \tag{4}$$

where m and n are the number of electrodes aligned in the z-direction and Δt is delay time. The point electodes located in "C" and "D" sections were selected to obtain $i_m(t)$ and $i_n(t+\tau)$, respectively. These positions were most appropriate for measuring the space-time correlation because the recirculating flow was expected to appear most definitely there. An example of space-time correlation measurement is

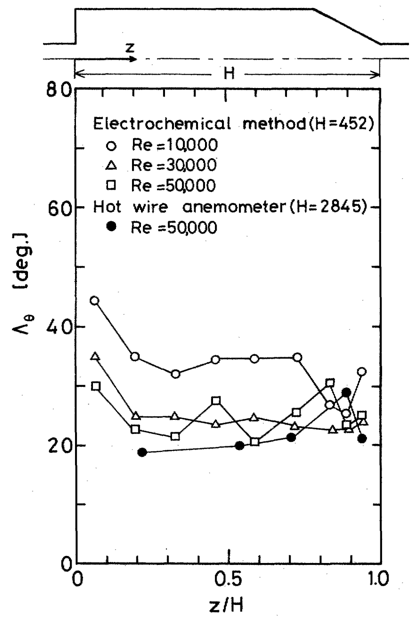

Fig. 4. Effect of Reynolds number on the integral scale of circumferential space correlation measured for "L" type test section

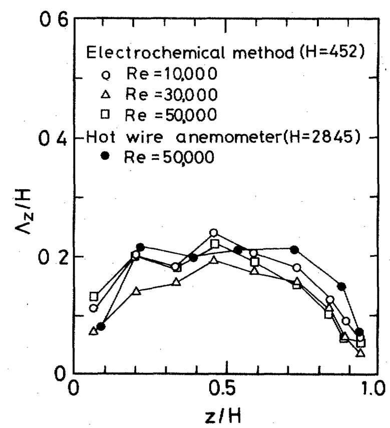

Fig. 5. Integral scale of longitudinal space correlation measured for "L" type test section

shown in **Fig. 6**. The delay time, Δt_{max}, at which R_{zt} has the maximum value is easily found. This means that the fluid element observed at "D" position is most probably observed again at "C" position after Δt_{max}. So the recirculating velocity may be determined by dividing the distance between "D" and "C" positions by Δt_{max}. As rather a small number of data size enabled us to determine easily the maximum space-time correlation point, the data size of each run was reduced to 1500, and ten individual data of Δt_{max} measurement were averaged to obtain the mean maximum delay time. The experimental results are shown in **Table 1**. This table indicates that the recirculating velocity along the side wall of test section is around 16 to 23% of the averaged velocity of the inlet jet. The recirculating velocity normalized by inlet jet velocity corresponds well to the recirculating

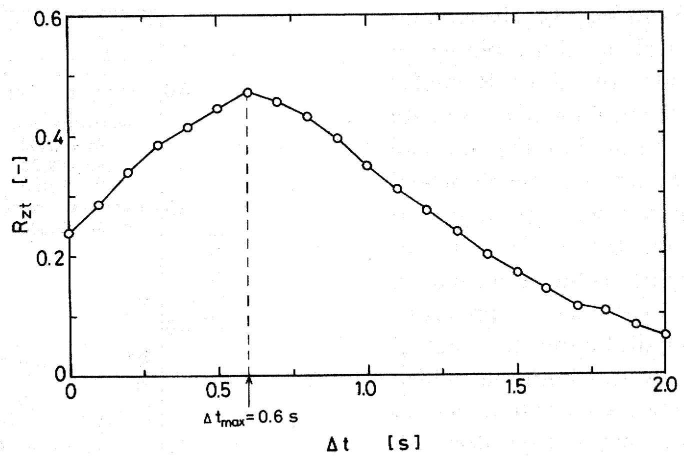

Fig. 6. Space-time correlation coefficient at $Re = 10^4$. The test section is "L" type

Table 1. Recirculating velocity determined by space-time correlation measurement

Re [–]	Δt_{max} [s]	U_r [m/s]	U_0 [m/s]	U_r/U_0 [–]
10,000	1.24	0.049	0.21	0.23
30,000	0.58	0.105	0.64	0.16
50,000	0.34	0.179	1.06	0.17

velocity determined by hot-wire anemometry reported in the previous paper[6].

2.3 Space distribution of recirculating eddy

According to the discussion given above, we can say that quite a large recirculating eddy, the scale of which in the longitudinal direction is around 20% of the total chamber length H, and the circumferential scale of which is around 40~60 degrees ($=2\Lambda_\theta$), moves along the side wall of the test chamber in the upstream direction. The recirculating velocity of this large eddy is around 20% of inlet jet velocity. However, it is obscure how the individual recirculating eddy is produced. Recirculation may be produced by the repulsion force arising from the impingement of the inlet jet on the conically contracting wall. But no information has been available to determine whether the recirculating eddy is moving spirally or not. To answer this question, the signals from twelve circumferential electrodes at the same longitudinal cross section (at "D" position) were simultaneously A-D converted, and the results are shown in **Fig. 7**. The horizontal axis indicates the time sequence of every limiting current measurement. The instantaneous current signals were subdivided into three categories by the threshold levels $i/\sqrt{\overline{i^2}}=0.3$ and 1.0. The highest and intermediate current levels are indicated by solid areas and dotted areas, respectively. The areas where solid and dotted points gather together seem to represent the high-speed fluid element passing near the inner surface of chamber.*2 Quantitative comparison of scale determined from this diagram with the integral scales shown in Figs. 4 and 5 is impossible, because the values of threshold level are rather arbitrarily taken. However, it is evident that a large recirculating eddy does exist near the wall, and the possibility that the recirculating eddy moves spirally is small. Individual recirculating eddies seem to appear randomly in space.

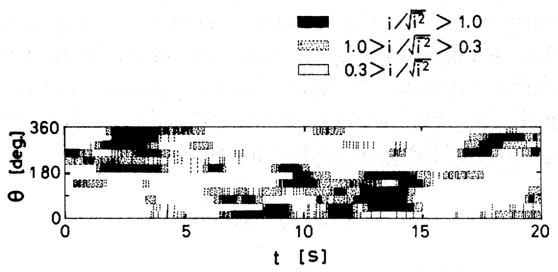

Fig. 7. Space distribution of recirculating eddy determined by simultaneous measurements of limiting current from twelve point electrodes in section D of "L" type test section ($Re = 10^4$)

2.4 Effect of test section length on the scale of recirculating eddy

As mentioned in the previous section, the three kinds of test sections shown in Fig. 1 were used in this study. Both the circumferential and longitudinal integral scales of space correlation were measured by means of the technique described above. The experimental results are shown in **Figs. 8** and **9**. The longitudinal integral scales of the "S" type test section was not obtained because the space correlation value of two adjacent electrodes aligned in the z-direction was so small that it was hard to assume the linear change

*2 If the velocity of a large eddy is constant, and if Talor's assumption for frozen turbulence is usable, the time change of eddy velocity may correspond to the spatial variation of eddy structure near the wall.

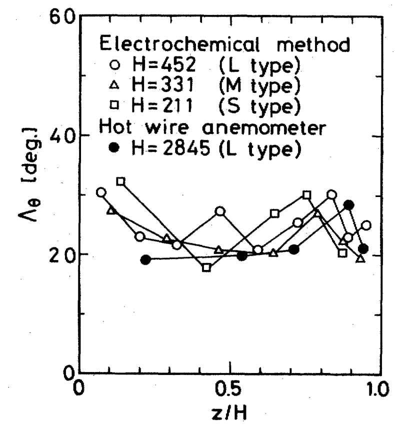

Fig. 8. Effect of test section length on the integral scale of circumferential space correlation at $Re = 5 \times 10^4$

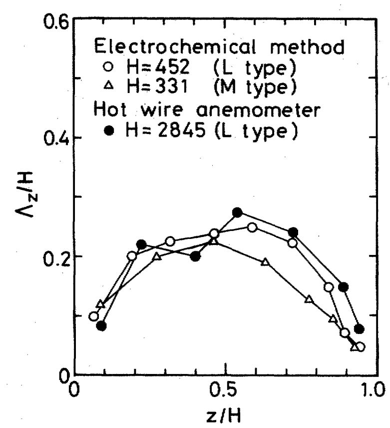

Fig. 9. Effect of test section length on the integral scale of longitudinal space correlation at $Re = 5 \times 10^4$

of space correlation value between these electrodes. The experimental results shown in Figs. 8 and 9 indicate that the length of test section has little effect on the scale of recirculating eddy. The expansion rate and the shape of the contraction section would mostly affect the recirculation characteristics. Further examination is required to clarify this point.

3. Conclusion

The recirculating flow characteristics in a confined space with axisymmetric sudden expansion followed by a conical contraction section were measured by means of an electrochemical method. Both space correlation measurement and simultaneously fluctuating current measurement of twelve circumferential electrodes revealed the scale and velocity of a large recirculating eddy. Overall features of the recirculating eddy are described as follows;

1. The longitudinal integral scale of the recirculating eddy is around 20% of test section length. The circumferential integral scale is around 40∼60 degrees ($=2\Lambda_\theta$).
2. The recirculating eddy moves upstream at a velocity of around 20% of inlet jet velocity. The recirculating eddy appears intermittently and randomly in space, and it moves straightly in the reverse z-direction. Spiral motion of the recirculating eddy was hardly observed.

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Nomenclature

D	= pipe diameter after expansion	[m]
d	= pipe diameter before expansion	[m]
H	= length of test section	[m]
i	= fluctuating component of limiting current	[A]
Re	= Reynolds number of pipe flow before expansion	[—]
R_z	= longitudinal space correlation coefficient	[—]
R_{zt}	= space-time correlation coefficient defined by Eq. (4)	[—]
R_θ	= circumferential space correlation coefficient defined by Eq. (1)	[—]
t	= time	[s]
Δt_{max}	= delay time at which R_{zt} shows maximum value	[s]
U_0	= average velocity of inlet jet	[m/s]
U_r	= velocity of recirculating eddy	[m/s]
z	= longitudinal distance from expansion point	[m]
θ	= circumferential angle	[degrees]
Λ_z	= integral scale of longitudinal space correlation defined by Eq. (3)	[m]
Λ_θ	= integral scale of circumferential space correlation defined by Eq. (2)	[degrees]

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