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Original Paper

PIV Measurement of Inlet and Outlet Flow of Contra-Rotating Small-Sized Cooling Fan

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Abstract

Contra-rotating rotors have been adopted for some of the cooling fans to meet the demand for the high pressure and large flow rate. Therefore, it is important to clarify its inlet and outlet flows by experiments for the high performance and stable operation. PIV measurements were conducted at the design and partial flow rates. In the present paper, the inlet and outlet flow conditions of the contra-rotating small-sized cooling fan with a 40mm square casing are studied by using PIV measurement. Furthermore, improvements of the flow condition and design guideline to increase the performance were discussed based on the experimental results.

Keywords: Cooling fan, PIV measurement, Internal flow, Contra-rotating rotor

1. Introduction

Data centers have been built because of spread of cloud computing, establishment of ubiquitous networking society and increase in rate of electric parts in machines. Then, electric power consumption in the data centers, IT devices and machines have been increasing significantly[1]. Electric power used for cooling of the IT devices for the data centers is as large as that used for the IT devices itself in the data centers and the electric power consumption of it is growing rapidly. There is a strong demand for a reduction of electric power consumption in above facilities and equipments from the point of view of the global warming and the energy savings[2]. Axial fans are used as cooling fans of servers and desk top computers. Then, researches of axial fans on fan noise and effect of inlet geometry were conducted[3],[4]. High power small-sized cooling fans; high pressure and large flow rate small-sized fan, are used for servers in the data centers and there is a strong demand to increase its power because of increase of quantity of heat from the servers. However, increase of the power by an increase of a fan diameter is restricted because of limitation of space. Therefore, high rotational speed design is conducted, and the rotational speed over 10,000min^{-1} is employed for the cooling fans of servers. Contra-rotating rotors have been adopted for some of the high power cooling fans to meet the demand for high power. On the other hand, low rotational speed design[5] and advantages on the performance of the contra-rotating fans and pumps were verified by experimental results[6]-[8]. The company's research and development period for the contra-rotating small-sized cooling fan was short and its internal flow condition was not clarified well. Therefore, the performance of each front and rear rotor and internal flow condition were investigated by the numerical analysis[9],[10]. But there was little experimental result related to the flow condition of the contra-rotating cooling fan having a diameter smaller than 100mm[11]. On the other hand, the design flow rate of the cooling fans is set by the resistance called the system impedance, which is decided by the PC case and layout of the electrical parts. Then, it can be operated at the off-design flow rate because the actual operating flow rate does not accord with the design one. Therefore, PIV measurements were conducted at the design and off-design flow rates for the inlet and outlet flow conditions of the contra-rotating small-sized cooling fan.

In the present paper, the PIV measurement results for the inlet and outlet flow conditions of the contra-rotating small-sized cooling fan at the design flow rate and the inlet flow condition in partial flow rates with positive slope of the performance curve were shown. Furthermore, improvements of the flow condition and design guideline to increase the performance were discussed based on the experimental results.

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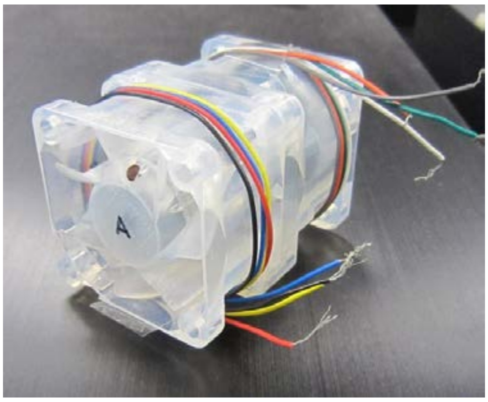
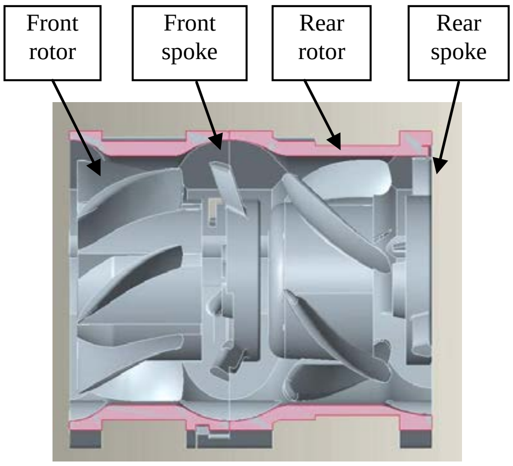
2. Experimental Apparatus and Method

The test fan and the primary dimensions of the high power contra-rotating small-sized axial fan(R40W-A) are shown in Fig.1 and Table 1 respectively. The rotors of R40W-A was set in the 40mm square casing, and a hub tip ratio of the front and rear rotors were D_{hf}/D_{tf}=25mm/37.2mm=0.67 and D_{hr}/D_{tr}=26mm/37.2mm=0.70 respectively. The design flow rate was Q_d=0.55m^3/min and a tip clearance c=0.6mm. The design rotational speed of the front and rear rotors of R40W-A were extremely high as N_f=15000min^{-1} and N_r=14000min^{-1}. Figure 2 shows a schematic diagram of an experimental apparatus. The experimental apparatus was designed based on the Japanese Industrial Standard and air blown in a test section passed the rotors, a chamber, a measurement duct and a booster fan and blew out in the ambient atmosphere. Each rotor was driven by a brushless motor set inside of the hub and the motor was supported by spokes connected to the casing. The rotational speed of each rotor was kept constant (N_f=15000min^{-1}, N_r=14000min^{-1}) by a PWM control using a function generator when a performance test was conducted. Fan static pressure (ΔP) was measured by pressure difference between static holes downstream of the rotor installed on the chamber and ambient air. Further, the rotational speed was evaluated using a pulse of the motor measured by an oscilloscope. The flow rates were measured by an orifice meter set at the measurement duct and the pressure curves from a cutoff flow rate to large flow rate were investigated in the experiment.

A schematic diagram of PIV system and a test section for PIV measurement are shown in Fig.3 and Fig.4 respectively. FlowMaster Stereo-PIV by LaVision was used for PIV measurement. The test section was designed the same as the experimental apparatus for the performance test, based on JIS B8330 and the whole test section for PIV measurement was made of acrylic resin. For the test section to be filled with tracer particles, the experimental apparatus for PIV measurement was a closed circuit and the flow rate was controlled by a valve installed in the circuit duct. Static pressure taps were set 200mm upstream of the fan inlet on a front chamber wall and 80mm downstream of the fan outlet on a rear chamber wall and the fan static pressure was measured by the static pressure difference between them. Then, the flow rate of PIV measurement test was calculated by the fan static pressure. It was difficult to conduct PIV measurement at the fan inlet using the front chamber in Fig.4, so the fan placement was turned over and the measurement at the fan inlet was conducted using the rear chamber. The double pulse YAG laser with 135mJ power was used as a light source and double pulse timing widths(repetition rate) were set as 20μs, 7μs(5kHz, 14kHz) according to the range of the measurement velocity. The phase locked averaged data were measured by inputting a trigger pulse from the rotor to PTU(Programmable Timing Unit). The measurement planes were meridional planes in vertical direction for the fan inlet and outlet and its area were about 58mm×58mm because the calibration plate size was 58mm×58mm. Tracer particles were propylene glycol with particle diameter 0.3-1.0μm. Two CCD camera with its resolution 2048×2048 pixels were used and velocity vector and vorticity distribution were calculated by the PIV measurement software DaVis(Lavision).



(a) Picture of R40W-A



(b) Sectional view of R40W-A

Fig.1 Test fan (R40W-A)

Table 1 Primary dimensions of rotors

		Hub	Mid	Tip
Front Rotor	Diameter [mm]	25	31.1	37.2
	Blade Number	7		
	Solidity	1.61	1.4	1.22
	Stagger Angle [deg]	18.2	31.2	36
Rear Rotor	Diameter [mm]	26	3.16	37.2
	Blade Number	5		
	Solidity	1.03	1.17	1.1
	Stagger Angle [deg]	40.6	40	45.5

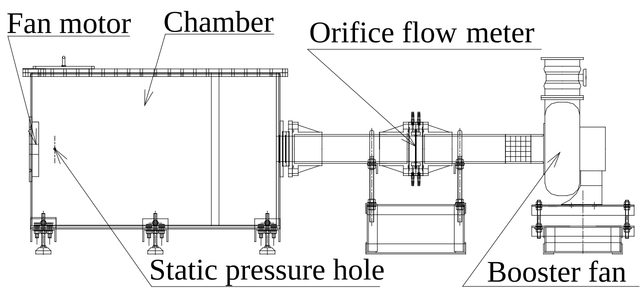


Fig.2 Schematic diagram of experimental apparatus

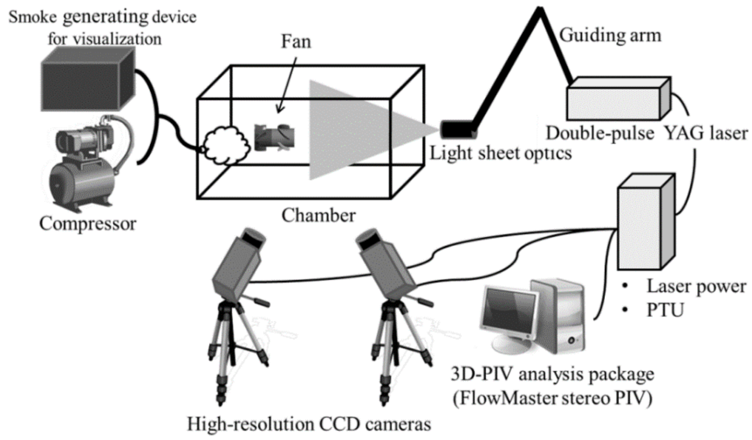


Fig.3 Schematic diagram of PIV system

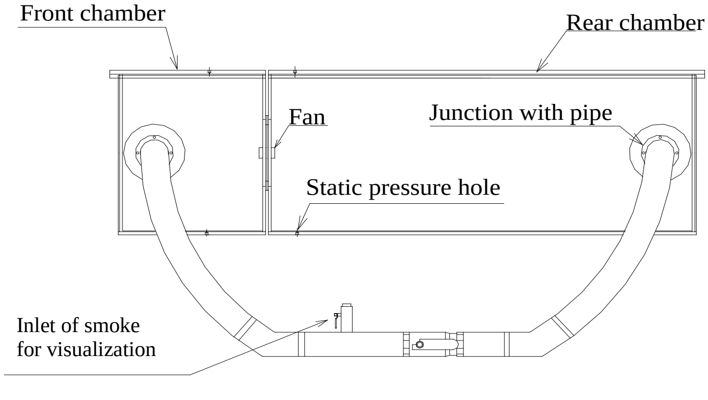


Fig.4 Schematic diagram of test section

3. Results and Discussions

3.1 Fan static pressure curve

The pressure curve of R40W-A obtained by the experiment at the design rotational speed (N_f=15000min^{-1}, N_r=14000min^{-1}) is shown in Fig.5. A horizontal axis is flow rate Q and a vertical axis is fan static pressure ΔP_s. The test fan showed the negative slope of the pressure curve from the design flow rate Q_d=0.55 m^3/min to the maximum flow rate Q=1.08 m^3/min and the maximum fan static pressure ΔP_s=510Pa was obtained at the design flow rate Q_d=0.55 m^3/min. A positive slope of the pressure curve appeared from a partial flow rate Q=0.50 m^3/min to the design flow rate Q_d=0.55 m^3/min. After that, the pressure curve became flat in partial flow rates region Q=0.35-0.50 m^3/min. Then, the positive slope of the pressure curve appeared again in partial flow rates region Q=0.25-0.35 m^3/min. The flow rate became unstable and vibration of the circuit duct and large noise were generated in the flow rate range showing the positive slope of the pressure curve. It was confirmed that the operating conditions of the test fan were in severe condition as the design fan static pressure was set extremely high and the design flow rate was near the flow rate range with the positive slope of the fan static pressure curve.

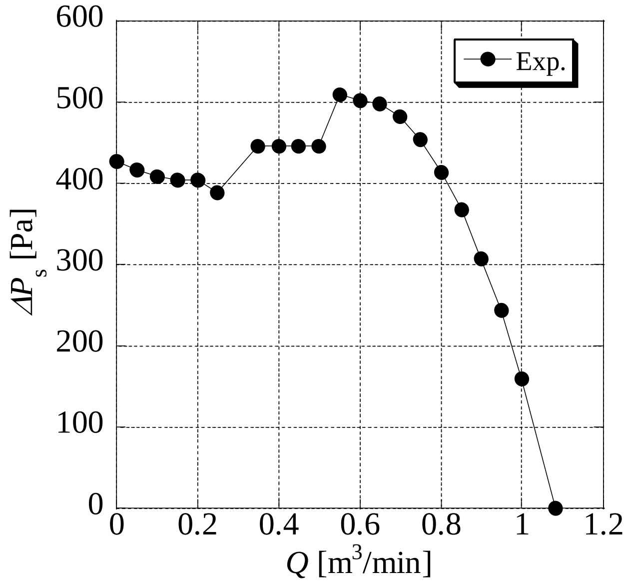


Fig.5 Static pressure curve

3.2 PIV measurement results at design flow rate

Figure 6 shows the three velocity components vectors inside a light sheet on the meridional plane in a vertical direction at the design flow rate Q_d=0.55m^3/min by PIV measurement. The measurement area in Fig.6 is the fan inlet and a rotational direction of the front rotor is down side of the paper. The main flow direction is right side of the paper and the vector shows only the direction of the air and the magnitude of the velocity are shown by a gray scale. It was found in Fig.6 that the velocity increased gradually 25mm upstream of the fan inlet and it reached 5m/s at the inlet of the front rotor as shown in circles of Fig.6. The air was sucked from both axial and radial direction, however, the velocity decreased on the chamber wall at the fan inlet. Figure 7 shows the three velocity components vectors on the meridional plane at the fan outlet. The flow rate and main flow direction are the same in Fig.6. The strong jet over 20m/s was generated at the rear rotor outlet and back flows occurred downstream of the rear rotor hub and on the chamber wall of the rear rotor. Then, the jet became uniform gradually with its diffusion. The vorticity distribution and velocity vectors at the fan inlet and outlet obtained by PIV measurement are shown in Fig.8. The axis of the vorticity is perpendicular to the meridional plane and a crock-wise direction is a positive. The flow rate and main flow direction are the same in Fig.6. The magnitude of the vorticity were relatively large at the high velocity region near the front rotor inlet shown as circles in Fig.8. The fan static pressure was high and flow rate was large for the test fan, so the inlet velocity was high and radially inward flow was induced near the fan inlet. In addition to that, the inlet bell mouse of the casing should be as small as possible because of the limitation of the space. As a result, the vortex was generated at the fan inlet even at the design flow rate. On the other hand, in the case of the fan outlet, the vorticity became high in boundary regions between the strong jet region at the outlet of the rear rotor and the back flow regions downstream of the rear rotor hub or the chamber wall shown as circles in Fig.8. It could be possible to

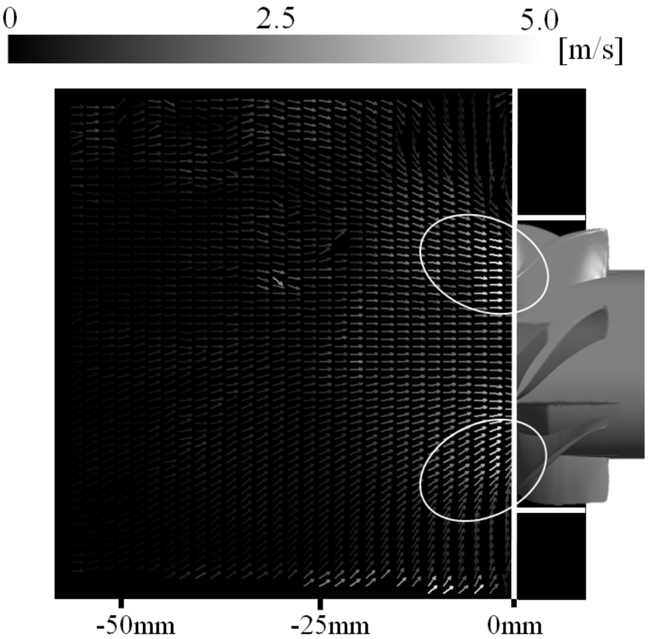


Fig.6 Velocity vectors at inlet of front rotor (Q_d=0.55m^3/min)

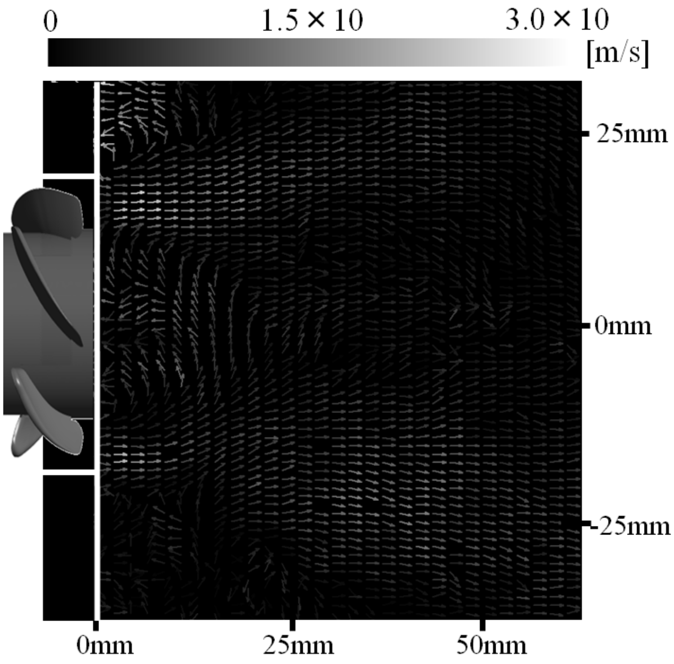


Fig.7 Velocity vectors at outlet of rear rotor (Q_d=0.55m^3/min)

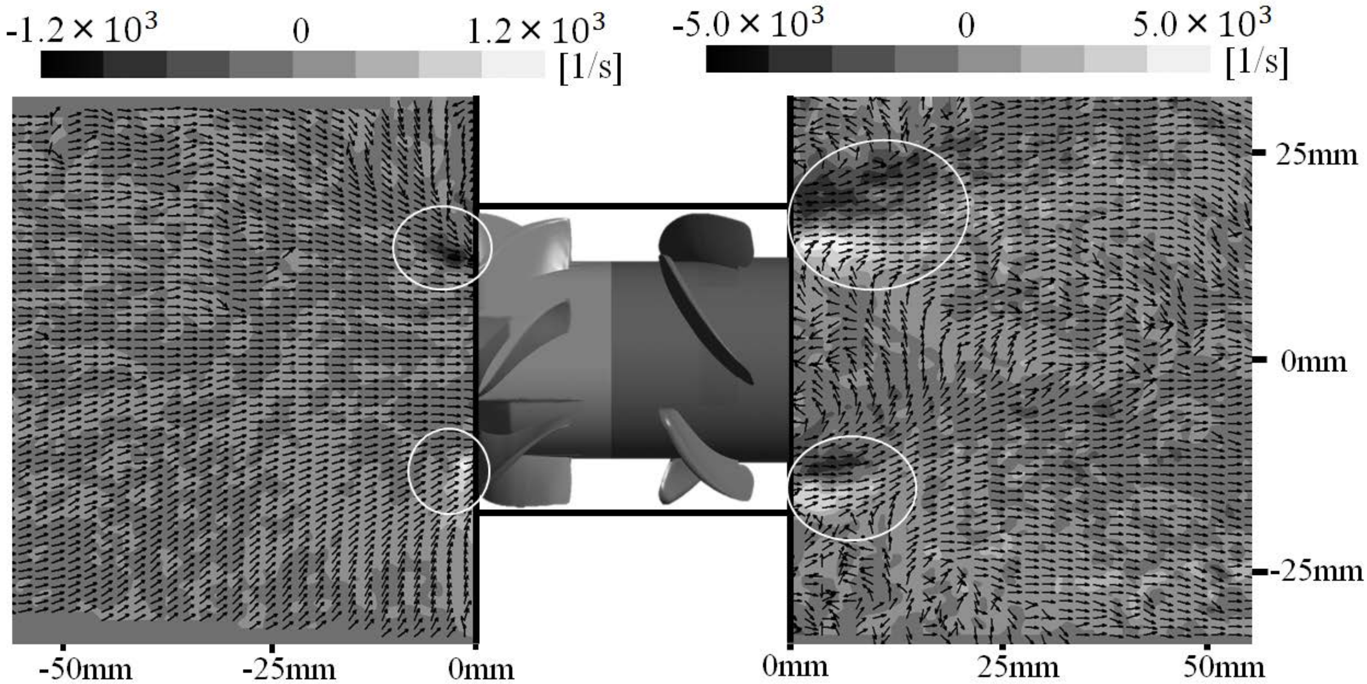


Fig.8 Vorticity and velocity vectors (Q_d=0.55m^3/min)

reduce the loss at the fan inlet and outlet by suppressing the sudden increase of the velocity at the fan inlet, local high velocity regions at the fan inlet and outlet, and strong shear flow between the high velocity region and back flow region at the fan outlet because the vortex would cause the total pressure loss. It was considered that the fan inlet and outlet flow condition could be improved by making uniform flow with the modified fan inlet bell mouse shape and suppressing the local high velocity with the modified casing outlet shape and rear rotor hub shape.

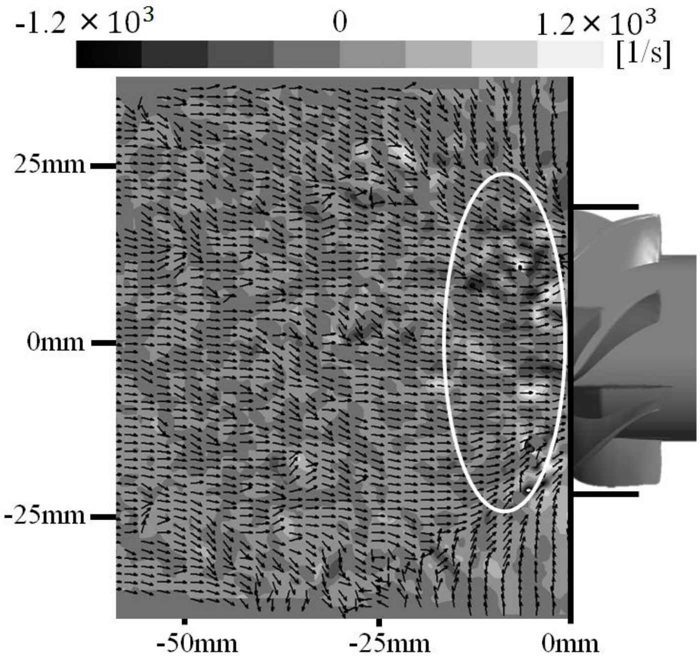


Fig.9 Vorticity and velocity vectors at inlet of front rotor (Q=0.50-0.55m^3/min)

3.3 PIV measurement results in partial flow rates

The vorticity distribution and velocity vectors at the fan inlet obtained by PIV measurement are shown in Fig.9. The axis of the vorticity is perpendicular to the meridional plane and a crock-wise direction is a positive. The flow rate is in unstable flow rate region Q=0.50-0.55 m^3/min, where the flow rate fluctuates. It was difficult to measure the flow condition at the fan outlet in this flow rate region. Many high vorticity regions were observed in the unstable flow rate region shown as a circle in Fig.9 and the velocity vectors weren't uniform at the fan inlet. It could be possible to show the instability of the flow condition by PIV measurement results.

4. Concluding Remarks

The flow conditions of the contra-rotating small-sized cooling fan at the fan inlet and outlet were investigated by PIV measurement. As a result, the following conclusions were obtained.

The vorticity was relatively high at the high velocity region near the front rotor inlet. On the other hand, in the case of the fan outlet, the vorticity became high in boundary regions between the strong jet region at the outlet of the rear rotor and the back flow regions downstream of the rear rotor hub or the chamber wall. It was considered that the fan inlet and outlet flow condition could be improved by making uniform flow with the modified fan inlet bell mouse shape and suppressing the local high velocity with the modified casing outlet shape and rear rotor hub shape.

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Nomenclature

c	Tip clearance [mm]
D_h	Diameter of hub [mm]
D_t	Diameter of tip [mm]
N	Rotational speed [min^{-1}]
N_d	Design rotational speed [min^{-1}]
ΔP_s	Fan static pressure[Pa]
Q	Flow rate [m^3/min]
Q_d	Design flow rate [m^3/min]
r	Radius [mm]

Subscripts

f	Front rotor
r	Rear rotor
d	Design point

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