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Performance assessment of various fan ribs inside a centrifugal blower

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A B S T R A C T

This study aims towards the development of an optimised design of a centrifugal blower consisting of various fan ribs, based on performance assessments following changes in the shape of its internal components. Various components, such as the external cases and the rotating fan ribs placed in a variety of operating conditions, are evaluated numerically and experimentally. Evaluation is based on performance parameters, including the inlet and outlet pressures, flow rate, torque, and power of the centrifugal fan. The numerical analysis suggests that the combination of the multiple rotating frame method and the standard k-ε turbulence model was appropriate for simulation of the internal flow characteristics and for power prediction. The numerical results were compared with tests under carefully designed experimental conditions. Based on the results and depending on the exit shape of the fan, the flow rate gradually increased to a value 7% higher than the existing model. The experimental and the numerical calculation results were in good agreement, particularly at the exit boundary condition at atmospheric pressure. In addition, among the four different impellers studied, the fan type with forward-curved fan ribs was associated with the best performance, reaching a maximum flow rate of 2.2 m^3/min and a torque of $0.09 N \cdot m$.

1. Introduction

The world demand for energy is rapidly increasing. We need energy to warm our homes, to cook our meals, to travel and communicate, and to power the offices or factories. Alongside with the rapid change of energy systems (e.g., primitive coal burners to oil or recently gas boilers and from central heating system to discrete heating system), the appliance markets of high performance boiler system have also been significantly increased. It has been requiring to develop nationally the environment-friendly and high efficiency equipment by considering simultaneously both the gradually higher prices of importing energy according to the depletion of fossil fuels and the environmental problems such as air pollution and global warming.

Recently, the total world heating (especially, gas-fired) boiler market was estimated around 10 billion dollars and 12 million units in 2006 and expected to grow at a moderate rate over the next decades [1]. The UK is the biggest market in both value and volume terms, followed by South Korea and Italy. In a wide range of industrial and residential home applications of energy system, the sales business of the boilers must adhere to a market oriented strategy, closely relying on the scientific and technological innovation in the national energy and environmental policy under the guidance of restructuring the enterprises, and product mix, manufacture and sale of boilers in order to meet highly competitive market demand.

One of the methods to increase the efficiency of the boiler is to achieve a complete combustion, which not only increases the efficiency of a gas-fired boiler, but also reduces the production of environmental contaminants. For complete combustion in the boiler, appropriate working conditions should be maintained, and this can be achieved by increasing the combustion time and using an appropriate mixture (i.e. stoichiometric mixture) of air and fuel. Therefore, it is crucial to understand which modules and components in the system are highly effective and designed for obtaining the best operating conditions. One of the core components in the boiler is the centrifugal fan, which is widely used to provide air to the boiler for combustion. Depending on the shape and size of these fans (i.e. fan ribs or impellers), the performance of the boiler can be improved. Therefore, in order to realize fan ribs with high performance and efficiency, a systematic design approach must be taken at the prototype stage.

A lot of works have been made to get an optimized design of the centrifugal fans in terms of the clearance/gap between internal

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Nomenclature

Greek symbols

α	static pressure ratio
β	diameter ratio
μ	dynamic viscosity
ν	kinematic viscosity
ρ	air density
ρ_I	air density at the fan inlet
ρ_N	air density at the nozzle
σ	turbulent Prandtl number
θ	azimuth angle
ε	dissipation rate

Roman symbols

A	cross-sectional area
BC	backward-curved
c	constant
C_p	pressure coefficient
D_N	nozzle diameter
f	other body forces
FC	forward-curved
g	acceleration due to gravity
k	kinetic energy
K	nozzle factor
L	length of a fan rib (from a to b)
p	static pressure
p_B	barometric pressure
$\triangle p_N$	nozzle differential pressure
p_S	gauge static pressure
Q	flow rate
Q_r	reference flow rate
R	gas constant
T_A	ambient temperature
T_N	nozzle inlet air temperature
u,V	velocity
V_{in}	velocity at fan inlet
x_i	Cartesian coordinates
z	elevation of the point

Superscripts

$\bar{\ }$	time averaged
$'$	fluctuation variable

Subscripts

i,j	vector indices
in	fan inlet
out	fan exit
r	reference

components, the shape and size of fan ribs and the internal radiated fan noise, etc. Regarding the effect of clearance between hub and volute, Engeda et al. [2] studied the centrifugal pump with the sensitivity factor of tip clearance loss depending upon pump specific speed. They observed in the experiment that the pump with a specific speed of 57 was highly insensitive to the varying tip clearance and could be regarded as an ideal design for semi-open centrifugal pump impeller. Cao and Chu [3] reported that volute width and hub-volute clearance had a significant effect to the performance of centrifugal fan. In order to control the flow rate and the noise level, Bayomi et al. [4] reported that the straightener at the inlet of centrifugal blower increased the flow rate and reduced noise revel for the radial and backward impellers. The effect of straighteners on the fan performance depends mainly on the exit blade angle. Son et al. [5] tried to observe the influence of bell mouth radius and inlet radius on the flow rate of a centrifugal blower by using CFD and parallel experiments, and they observed that the bell mouth and inlet radii had a significant effect on the flow rate.

Datong et al. [6] tried to observe that the increase of the clearance between hub and volute made the higher flow rate and reduced the radiated noise revel. In addition, Chunxi et al. [7] found that the increment of fan ribs in diameter with the keeping the size of volute (less clearance between fan ribs and volute) induced the loss of gap flow and the gain of flow rate and pressure, which increased the shaft power and sound pressure level, while the efficiency of fan ribs decreased. Of course, the higher noise level was caused by the reduced fan ribs-volute gap.

Regarding the external shape and size of the centrifugal fans, Cau et al. [8] showed that a severely distorted primary flow in the exit region (i.e., tongue area), produced an inefficient performance, which seemed to be caused by earlier flow separation on the suction side, and poor matching between impeller outlet and volute tongue. Gong et al. [9] tested the detailed velocity field near the volute tongue of a forward-curved (hereafter, FC) multi-blade fan using PIV (Particle Image Velocimetry) and drew a conclusion that the matching between impeller outlet flow pattern and volute tongue had a substantial influence on the flow loss in the volute.

Engin et al. [10] tried to minimize the tip clearance loss with the changing impeller shape experimentally. Among three different shapes of fan ribs, they observed that the backward-curved (hereafter, BC) fan was poorly dependent upon the tip clearance. Ishida and Senoo [11] measured the pressure distribution along the shroud for three types of centrifugal impeller at seven different values of tip clearance and found that the pressure loss due to the tip clearance was relatively small in the region where the relative velocity was nearly constant. They also underlined that this loss was proportional to the pressure rise caused by the deceleration of the relative velocity. In addition, Cui et al. [12] reported that the complex impeller with long, mid and short blades can improve the velocity distribution and reduce the back flow. Kim et al. [13] found that two splitter blades generated the reverse-flow regions in the blade passage, which can control the numbers of main blade and splitter blades. Karanth and Sharma [14] reported that a smaller pressure fluctuation and higher flow rate at the exit was realized by a larger radial gap between the impeller and diffuser.

In an evaluation study of fan operation, Hillewaert and Braeumbussche [17] calculated the 3D unsteady flow for centrifugal compressors and obtained a reasonable agreement with PIV measurements. In addition, Meakhail and Park [18], Atif et al. [19], and Karanth and Sharma [14] compared CFD and the PIV measurements with the aim of understanding the flow interaction between the centrifugal fan impeller and diffuser, which might be able to explain the internal flow characteristics of the centrifugal fan. Cardillo et al. [15] and Elsheikh et al. [16] developed a model of a centrifugal fan by using the finite volume method and obtained reliable prediction results at peak pressure and efficiency conditions. Lee et al. [20] conducted a parametric study of pathways of a centrifugal fan with a double-inlet, double-outlet, double-width impeller to reduce power consumption while maintaining a specified output pressure at the volute exit. They found that the width of the impeller is almost linearly related to the total head from the