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A study on the flow field and local heat transfer performance due to geometric scaling of centrifugal fans

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ABSTRACT

Scaled versions of fan designs are often chosen to address thermal management issues in space constrained applications. Using velocity field and local heat transfer measurement techniques, the thermal performance characteristics of a range of geometrically scaled centrifugal fan designs have been investigated. Complex fluid flow structures and surface heat transfer trends due to centrifugal fans were found to be common over a wide range of fan aspect ratios (blade height to fan diameter). The limiting aspect ratio for heat transfer enhancement was 0.3, as larger aspect ratios were shown to result in a reduction in overall thermal performance. Over the range of fans examined, the low profile centrifugal designs produced significant enhancement in thermal performance when compared to that predicted using classical laminar flow theory. The limiting non-dimensional distance from the fan, where this enhancement is no longer apparent, has also been determined. Using the fundamental information inferred from local velocity field and heat transfer measurements, selection criteria can be determined for both low and high power practical applications where space restrictions exist.

1. Introduction

The widespread use of centrifugal fans in engineering has resulted in many geometric variations of designs in order to meet application requirements. Such applications range from large scale industrial dryers and air conditioning units, to smaller scale blowers for the purpose of augmenting heat transfer in portable electronics. The requirement of fans in the electronics industry has substantially driven the demand for high performance, low noise, and low cost units that can contribute to maintaining adequate component temperatures within space restricted environments. In addition, the continual increase in density of electronics within devices suggests that future cooling solution designs will be further limited by available space. Therefore, there is a necessity to address the topic of miniaturization within the area of thermal management, to prevent thermal issues from stalling the development of future technologies. This is reflected in recent literature examining such areas as phase change materials (Tan and Tso, 2004; Fok et al., 2010), thermo electric coolers (Wilson and Simons, 2005; Garimella et al., 2008), and microheat pipes (Langari and Hashemi, 2000). However, despite the widespread use of fan–heat sink combinations in electronics cooling, there is limited information available that fundamentally examines the influence of geometric scaling on the flow field and local heat transfer distributions produced by miniature centrifugal fans.

At larger scales, the extended use of centrifugal fans for fluid movement has resulted in detailed research into the performance attributes of many designs. Wu et al. (2008) investigated the velocity field at inlet, outlet, and tip leakage planes for a centrifugal design with seven unequally spaced blades that were also staggered at different angles along the blade span from hub to shroud. The authors present this design as an effective way to improve aerodynamic performance and reduce noise. High levels of positive and negative vorticity exist on fan outlet measurement planes indicating counter rotational vortices which were generated by the backward curved airfoil blades in rotation. The majority of the mass flow tended towards the impeller hub, with increased velocity fluctuations at the shroud side, aided by small vortices created by leakage flow near the impeller shroud. The influence of a scroll housing on the non-dimensional fan performance was noted as being insignificant at a certain flow coefficient, however below this point the scroll housing offered an increase in total pressure and efficiency, with a decrease in the same observed at the higher flow coefficients.

Yen and Liu (2007) used a phase-locked PIV technique to determine the outlet flow field of a shrouded centrifugal fan design which has dimensions suitable to laptop sized electronic applications. Two planes were considered in detail, and the exit flow from the shroud was shown to exit at an off-angle to the fan housing. This was similarly noted by Egan et al. (2009) in a study of the flow

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Nomenclature

A	surface area, m^2
a_r	fan aspect ratio
c	chord length, m
C	specific heat capacity, J/kg K
D	fan diameter, m
Dh	hydraulic diameter $\equiv 4\pi DH/2(\pi D + H)$, m
D_{in}	fan inlet diameter, m
$f_{\max}$	max. frequency detectible, Hz
FC	forward curved
H	distance between plates, m
H_f	fan profile height, m
h	heat transfer coefficient, W/m^2 K
I	current, A
k	thermal conductivity, W/mK
$NETD$	noise-equivalent temperature difference
Nu	Nusselt number
ΔP	static pressure difference, Pa
q''	heat flux, W/m^2
Q	volumetric flow rate, m^3/s
r	radial direction from fan center, m
r^*	non-dimensional distance from fan blade $\equiv ((r-(D/2))/Dh)/(\mathrm{Re}_{Dh}\,\mathrm{Pr})$
Re	Reynolds number
T	surface temperature, K
Tu	turbulence intensity $\equiv 1/2\sqrt{\overline{u'^2}+\overline{v'^2}}/U_{ex}$
u, v	radial, axial velocity components, m/s
u', v'	fluctuating component of velocity, m/s
U	velocity magnitude $\equiv \sqrt{u^2+v^2}$, m/s
U_{ex}	mean fan exit velocity, m/s
V	voltage, V
V_t	blade tip velocity, m/s
x, y, z	Cartesian coordinates, m
$\left(\overline{\ldots}\right)$	time average

Greek symbols

ε	emissivity
μ	dynamic viscosity, kg/m s
ω	fan rotation
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, $W/m^2\,K^4$
σ_h	normalized fluctuations in heat trans. coeff. $\equiv \sqrt{\overline{h'^2}}/h_{fc}$
τ	time, s
ϕ	flow coefficient
ψ	pressure coefficient

Subscripts

aw	adiabatic wall temperature, K
c	blade chord conditions as reference
c	conduction
f	foil (SS304)
fc	forced convection
gen	input
max	maximum
nc	natural convection
p	paint
r	radiation
∞	ambient

entering miniature heat sinks which were positioned adjacent to a shrouded centrifugal fan outlet. It was found that increases of up to 20% in the overall thermal performance of the miniature cooling solutions could be achieved by aligning the fan exit flow with the heat sink channels. This highlights the benefit of designing fan and heat sink collectively rather than separately as is commonly considered. The advantage of using a finless heat sink design at this scale over a conventional finned design was also another outcome of this work. Stafford et al. (2009a) showed that the thermal performance of the finless design is under predicted using laminar duct flow theory. It was hypothesized that unsteady flow structures generated by the centrifugal fan were conserved in the finless geometry, thereby promoting heat transfer. The finned design however, suppressed these flow features to the longitudinal direction, forming a closer representation with theory. The authors also presented a prediction tool to determine the cross over in design choice for finned and finless geometries.

Previous studies examining the bulk performance of rotating fan designs indicates a degrading effect on aerodynamic performance when fans are geometrically scaled below a critical point. Grimes et al. (2005) initially noted the adverse geometric scaling effect on the performance of an axial fan design. A datum fan design with a 120 mm diameter was geometrically scaled down to 1/3, which indicated a reduction in fan efficiency. Quin and Grimes (2008) examined the same designs including a 1/20 scale of the same axial fan design for a range of blade Reynolds numbers from 283 to 39,700 based on chord length and blade velocity at the mid-span. Below a Reynolds number of 1980, a viscous scaling effect was observed, where fan performance was adversely affected and could no longer be determined by the non-dimensional flow and pressure coefficients of the datum fan. Neustein (1964) also determined a Reynolds number effect on axial fan performance to occur below 2000. The resultant influence of this scaling effect on local heat transfer distributions using a miniature axial fan has recently been documented by Stafford et al. (2010a). In a complimentary study by Stafford et al. (2010b), a larger axial fan with different blade geometry and hub-tip ratio was found to produce similar surface heat transfer distributions. This was attributed to the similarity in motor support layout on the exit flow plane.

The miniaturization of centrifugal fan designs also results in a similar scaling effect on fan performance as shown by Walsh et al. (2009a, 2010). In the first study by Walsh et al. (2009a), the influence of fan profile scaling for fan diameters of 15–30 mm was examined to address the issues associated with implementing miniature fan designs in low profile applications. The fan characteristics of flow rate, pressure rise, and power consumption were experimentally measured while varying the blade profile alone. A low Reynolds number effect was noted at 650 based on chord length and blade tip velocity which resulted in a reduction of flow rate, and a simultaneous increase in power consumption over that predicted using conventional scaling laws (Bleier, 1997). At the miniature scale, these fan scaling laws were found to be valid only for fan aspect ratios between 0.12 and 0.17. In a separate study, Walsh et al. (2010) examined the same fan characteristics and range of fan diameters but in this case varying blade chord length. Similar trends in reduced fan performance were noted at low Reynolds numbers, and the authors applied simple boundary layer theory to determine the main contribution to this scaling effect for miniature fans. In doing so, the authors proposed an alternative empirical based correlation for determining the performance of centrifugal fan designs operating at low Reynolds numbers.

Aside from studies relating to fan flow and pressure characteristics, investigations into the acoustic emissions of centrifugal fan designs has also received attention (Wolfram and Carolus, 2010;