New Insights into the Swirling Flow in Turbine Blade Cooling Models Obtained via Magnetic Resonance Velocimetry

Vom Fachbereich Maschinenbau
an der Technischen Universität Darmstadt
zur
Erlangung des Grades eines Doktor-Ingenieurs (Dr.-Ing.)
genehmigte

Dissertation

vorgelegt von

Martin Bruschewski, M.Sc.

aus Langen (Hessen)

Berichterstatter:	Prof. Dr.-Ing. Heinz-Peter Schiffer
Mitberichterstatter:	Prof. Dr.-Ing. habil. Sven Grundmann
Tag der Einreichung:	02.08.2016
Tag der mündlichen Prüfung:	25.10.2016

Darmstadt 2017

D 17

Forschungsberichte aus dem Institut für Gasturbinen,
Luft- und Raumfahrtantriebe

Band 5

Martin Bruschewski

New Insights into the Swirling Flow in Turbine Blade Cooling Models Obtained via Magnetic Resonance Velocimetry

D 17 (Diss. TU Darmstadt)

Shaker Verlag
Aachen 2017

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Darmstadt, Techn. Univ., Diss., 2016

Printed in Germany.

ISBN 978-3-8440-5357-9
ISSN 2364-4761

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

Abstract

Magnetic Resonance Velocimetry (MRV) allows measurements of the three-dimensional velocity field in complex channels in which no other measurement technique can be applied. In particular, the combination of MRV with inexpensive rapid prototyping techniques allows fast measurement cycles of arbitrary designs. In this thesis, a recent engineering problem is used to demonstrate the usefulness of MRV for industrial design processes: the cyclone cooling of turbine blades. Cyclone cooling is a modern cooling concept which employs strongly swirling flows in the internal passages of the turbine blade. At the Reynolds numbers and high swirl intensities which are needed for cooling, the flow is characterized by strong anisotropic turbulence and instability. These features prohibit the use of simple turbulence models in CFD. Because of this reason, there is only scarce information available on the flow behavior in cyclone cooling systems. MRV provides a powerful means to gain a deeper understanding of the flow behavior in such systems. Based on a comprehensive parameter study with simplified non-rotating cyclone cooling models employing isothermal water as flow medium, it is examined how the flow reacts to changes in the main parameters of the system. A number of new findings are presented which underline the usefulness of MRV for such applications. In brief, it is found that the downstream condition of the cyclone cooling system is one of the most crucial parameters for the robustness of the system. For example, small changes at the channel outlet can lead to significant variations in the flow pattern inside the entire channel, leading to unpredictable changes in the cooling characteristics. Therefore, as a rule of design, the flow has to be made insensitive to these influences. A number of straight-forward measures are presented which provide the necessary conditions. The transferability of these findings from the simplified cyclone cooling models to the real application is verified by means of a numerical simulation and a realistic cyclone cooling system that is measured with MRV. In conclusion, this thesis demonstrates the potentials of MRV to contribute to quick and accurate design processes in the fluid mechanics industry. As a possible future scenario, MRV could be integrated in the actual layout of a turbine blade cooling system, or likewise to similar problems in engineering.

Vorwort des Herausgebers

Die Reihe Forschungsberichte aus dem Institut für Gasturbinen, Luft- und Raumfahrtantriebe gibt die Forschungs- und Entwicklungsfortschritte im Bereich der Turbomaschine an der Technischen Universität Darmstadt wieder. Aufgrund der starken Anwendungsorientierung in diesem Bereich der Forschung sind universitäre Fragestellungen Spiegelbild industrieller Entwicklungstrends.

Wechselnde politische, ökonomische und ökologische Rahmenbedingungen bestimmen hierbei aktuelle Entwicklungsschwerpunkte und bringen die Turbomaschine immer wieder an den Rand des technisch realisierbaren. Dadurch werden neue Erkenntnisse aus der Forschung nicht selten unmittelbar industriell umgesetzt.

In diesem Umfeld entstehen die industrie- und anwendungsnahen, wissenschaftlichen Arbeiten dieser Reihe. Sie beschreiben aktuelle Erkenntnisse aus experimentellen Untersuchungen und numerischen Simulationen, die am Fachgebiet für Gasturbinen, Luft- und Raumfahrtantriebe an der Technischen Universität Darmstadt gewonnen werden konnten.

Heinz-Peter Schiffer

Darmstadt, 2017

Acknowledgment

Over the past five years I have received support and encouragement from a great number of individuals. I am thoroughly grateful to my supervisors Prof. Dr.-Ing. Heinz-Peter Schiffer and Prof. Dr.-Ing. habil. Sven Grundmann who's guidance has made this a thoughtful and rewarding journey.
I would like to thank my fellow doctoral students at the Dept. of Mechanical Engineering in Darmstadt and the Dept. of Radiology in Freiburg for their support, feedback, and friendship. I would like to thank Daniel F., Florian W., Waltraud B., Robin S., Christopher B., Christian S. and Bernd J. for their feedback on various aspects of this thesis. I would like to thank the work shop staff for their precise work and the last minute favors. I would like to thank my friends for accepting nothing less than completion from me. I would like to thank my family for encouraging me in all of my pursuits. Last, but certainly not least, I would like to thank my wife Melanie and my daughter Mira for the most valuable support. You are my source of motivation.

This thesis was supported by the Bundesministerium für Wirtschaft und Technologie (BMWi) under grant number 20T1108C.

Contents

List of Figures

List of Tables

Nomenclature

Greek Symbols

α	swirl decay parameter: initial term
β	swirl decay parameter: exponential term
γ	gyromagnetic ratio
$\Delta\Phi$	phase difference between two or more images
$\Delta\Phi_n$	noisy phas1e difference
Δm_i	difference in i-th gradient moment between two measurements
δ_{ij}	Kronecker delta
δ_r	space encoding error
δ_u	velocity encoding error
ε_1	mean radius of swirl generator inlet
ε_2	eccentricity of orifice
ζ	vorticity
ζ^*	dimensionless vorticity
η	outward normal vector
Θ	flip angle of excitation
λ	thermal conductivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	fluid density
σ_Φ	standard deviation in image phase
$\sigma_{\Delta\Phi}$	standard deviation in phase difference data
σ_u	measurement uncertainty
σ_n	noise standard deviation
Φ	image phase, phase of reconstructed MRI signal
Φ_n	noisy image phase
φ	phase angle of spins, circumferential coordinate
Ω_L	fluid domain
ω_L	Larmor frequency of the nuclear spin

Latin Symbols

A	image magnitude, magnitude of reconstructed MRI signal
A_n	noisy image magnitude
B	flux density of external magnetic field
b	coil sensitivity
D	channel diameter
d_1	opening diameter of concentric orifice
d_2	inner diameter of ring orifice
$\mathbf{G}_s$	three-dimensional space encoding gradient
$\mathbf{G}_v$	three-dimensional velocity encoding gradient
g	pressure gradient
$\mathbf{k}$	three-dimensional k-space coordinate
L	channel length from swirl generator bottom to outlet
l_{V}	voxel size, resolution
M	net magnetization vector of an ensemble of spins
m_i	i-th gradient moment
N	number of receiver coils
Nu	Nusselt number
Nu_0	Nusselt number of fully developed flow
p	static pressure
p_{ref}	reference pressure
Q	volumetric flow rate
$\dot{q}''$	heat flux
R	channel radius
Re	Reynolds number
$\mathbf{r}$	three-dimensional spatial coordinate
R_b	mean bend radius
S	swirl number
S_0	initial swirl number as produced by the swirl generator
s	spin position
T_f	reference fluid temperature
T_w	wall temperature
t	width and depth of swirl generator inlet
U_b	bulk flow velocity
u	spin velocity, measured velocity
V_{V}	voxel volume
$venc$	encoding velocity of the MRV acquisition
Z	complex MRI signal, complex image
Z_n	noisy complex image

Abbreviations

AWGN	additive white Gaussian noise
BW	bandwidth of MRI receiver system
CFD	computational fluid dynamics
CFL	cell-Courant number
FFT	fast Fourier transform
FID	free induction decay
FLASH	fast low angle shot MRI acquisition sequence
FOV	field of view of MRI acquisition
LDV	laser Doppler velocimetry
LES	large eddy simulation
MRI	magnetic resonance imaging
MRV	magnetic resonance velocimetry
NEX	number of averages
NEXref	number of reference scans
PIV	particle imaging velocimetry
RANS	Reynolds averaged Navier–Stokes
RF	(radio frequency) spin excitation pulse
ROI	region of interest in measured image
SNR	signal-to-noise ratio
SOS	sum-of-squares combination of multiple images
TA	total acquisition time
TE	echo time
TR	repetition time
WM	weighted-mean combination of multiple images

Mathematical Operators

$\langle \dots \rangle$	sample mean
$(\dots)^*$	complex conjugation
$\angle\{\dots\}$	angle of complex number
$\nabla\{\dots\}$	nabla operator
$\arg\max\{\dots\}$	argument of the maximum
$\mathfrak{F}\{\dots\}$	Fourier transform
$I_i\{\dots\}$	i-th modified Bessel function of first kind
$\mathcal{N}\{\sigma\}$	white Gaussian noise with standard deviation σ
$\mathrm{N.\,I.}\{\dots\}$	next integer
$p\{\dots\}$	probability density function
$\mathrm{Var}\{\dots\}$	sample variance