Centrifugal Pumps

Johann Friedrich Gülich

Centrifugal Pumps

Second edition

Springer

Johann Friedrich Gülich
johann.guelich@bluewin.ch

ISBN 978-3-642-12823-3 e-ISBN 978-3-642-12824-0
DOI 10.1007/978-3-642-12824-0
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2010928634

Cover design: eStudio Calamar S.L., Berlin/Figueres

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Life is linked to liquid transport, and so are vital segments of economy. Pumping devices – be it the human heart, a boiler feeder or the cooling-water pump of a motorcar – are always part of a more or less complex system where pump failure can lead to severe consequences. To select, operate or even design a pump, some understanding of the system is helpful, if not essential. Depending on the application, a centrifugal pump can be a simple device which could be built in a garage with a minimum of know-how – or a high-tech machine requiring advanced skills, sophisticated engineering and extensive testing. When attempting to describe the state-of-the-art in hydraulic engineering of centrifugal pumps, the focus is necessarily on the high-tech side rather than on less-demanding services even though these make up the majority of pump applications.

Centrifugal pump technology involves a broad spectrum of flow phenomena which have a profound impact on design and operation through the achieved efficiency, the stability of the head-capacity characteristic, vibration, noise, component failure due to fatigue, as well as material damage caused by cavitation, hydro-abrasive wear or erosion corrosion. Operation and life cycle costs of pumping equipment depend to a large extent on how well these phenomena and the interaction of the pump with the system are understood.

This book endeavors to describe pump hydraulic phenomena in their broadest sense in a format highly relevant for the pump engineer involved in pump design and selection, operation and troubleshooting. Emphasis is on physical mechanisms, practical application and engineering correlations for real flow phenomena, rather than on mathematical treatment and theories of inviscid flow.

The present 2nd English edition has been supplemented with some recent research results on hydraulic excitation phenomena. Additional information has been provided on: sewage pump design data, hydraulic unbalance of single-channel impellers, torsional vibrations and turbine calculations. Printing errors were corrected and some additions were done in most of the chapters.

The first (1999) and second (2004) editions of this book were written in German. The third edition in German is due to appear in the 1st semester of the year 2010.

Villeneuve (Switzerland), January 2010

J.F. Gülich

Acknowledgements

The 1st English edition owed its existence to the initiative and sponsoring of the management of Sulzer Pumps. For this I am most grateful to Dr. A. Schachenmann who initiated the project, R. Paley and Dr. R. Gerdes.

The book benefited much from the help which I got from many colleagues at Sulzer Pumps in the US and the UK to whom my sincere thanks are extended. Most important were the reviews of the English text. M. Cropper was instrumental in this activity. S. Bradshaw, R. Davey, Dr. J. Daly, D. Eddy, M. Hall, Dr. A. Kumar, P. Sandford, D. Townson, and C. Whilde reviewed individual chapters.

J.H. Timcke meticulously checked most of the 1st English edition for consistency with the 2nd German edition and made many suggestions for making the text and figures easier to understand. Mrs. H. Kirchmeier helped with the figures and computer problems. Last but not least, my wife Rosemarie Gülich was a tremendous help in checking and improving the final text.

I am grateful to various individuals who provided me with literature and granted permission for using figures: Prof. Dr.-Ing. F. Avellan, Dr. M. Farhat, Dr. O. Braun and S. Berten from the Ecole Polytechnique Lausanne; Prof. Dr.-Ing. D.H. Hellmann, Prof. Dr. Ing. M. Böhle and H. Roclawski from the Technical University Kaiserslautern; Prof. Dr.-Ing. G. Kosyna, Prof. Dr.-Ing. habil. U. Stark, Mrs. Dr.-Ing. I. Goltz, Mrs. P. Perez, Dr. Ing. H. Saathoff from the Technical University Braunschweig; C.H. van den Berg, MTI Holland; Prof. Dr.-Ing. H. Wurm, Wilo Dortmund; Dr. P. Dupont, Sulzer; U. Diekmann, Wilo-Emu and A. Nicklas, Sterling Fluid Systems.

The 1st and 2nd editions benefited from the reviews of individual chapters provided by: Dr.-Ing. G. Scheuerer, ANSYS München and Dr. P. Heimgartner, W. Bolliger, W. Schöffler, Dr.-Ing. W. Wesche, Dr. P. Dupont, S. Berten, G. Caviola, E. Leibundgut, T. Felix, A. Frei, E. Kläui (all from Sulzer).

The following organizations or individuals kindly granted permission for using figures:

- Sulzer Pumps Ltd, Winterthur
- Mr. T. McCloskey, Electric Power Research Institute, Palo Alto, CA, USA
- VDMA, Frankfurt
- VDI-Verlag, Düsseldorf
- Mr. J. Falcimaigne, Institut Français du Pétrole, Paris
- ASME New York

The appropriate references are given in the figure captions.

Hints for the reader

The text is written according to US-English spelling rules.

As is customary in English publications, the decimal *point* is used (I had to substitute points for commas in all figures, equations and graphs and hope not to have overlooked too many of them). To avoid confusion of readers used to the decimal *comma*, large figures are written in the form of 6’150’000.00 (instead of 6,150,000.00)

Nomenclature: Unfortunately there is no commonly accepted nomenclature and use of technical terms. As far as possible I have consulted various standards as to the most accepted terms. The reader is referred to the extensive list of symbols given below. For easy reference, this list defines the chapters, tables or equations where the respective symbols are introduced. A number of subscripts from the German original were left unchanged since replacing them by meaningful English abbreviations involved too much of a risk of overlooking some items which are used throughout the text and the equations.

Conventions: Equations, tables and figures are numbered by chapter. The geometrical dimensions of impellers, diffusers and volutes are defined in Table 0.2.

To improve the readability, simplified expressions have sometimes been used (for example “volute” instead of “volute casing”). In order to avoid monotonous repetition of technical terms, synonyms are (sparingly) employed.

Formulae frequently used in practice were gathered in tables which present the sequence of calculation steps required to solve a specific problem. These tables help to find information quickly without looking through a lot of text; they also facilitate programming. The equations presented in the tables are labeled by “T”. For example Eq. (T3.5.8) refers to equation 8 in table 3.5. Most of the tables are labeled as “Table 6.1”, for example. Some “data tables” are referred to as “Table D6.1” for instance; this subterfuge was made necessary by the layout of the German editions which contained “tables” and “plates”.

Mathematical expressions: Empirical data in the literature are frequently presented in graphical form. In most cases such data are given in this book in the form of approximate equations in order to ease programming and to save space.

For reasons of simplicity the upper limit of a sum is not specified when there can be no doubt about the variable. For example, $\sum_{st} P_{RR}$ stands for $\sum_{i=1}^{i=z_{st}} P_{RR,i}$ and represents the sum of the disk friction losses in all stages of a multistage pump.

An equation of the form y = a×exp(b) stands for $y = a \times e^b$, where “e” is the base of the natural logarithm.

The symbol ~ is used for “proportional to”; for example, $P_{RR} \sim d_2^5$ stands for “the disk friction loss is proportional to the 5th power of the impeller diameter”.

Frequent reference is made to the specific speed n_q which is always calculated with n in rpm, Q in m^3/s and H in m. For conversion to other units refer to Table D2.1 or Table 3.4. For simplicity, the specific speed n_q is treated as a dimensionless variable even though this is not true.

Many diagrams were calculated with MS-Excel which has limited capabilities for graphic layout. For example: 1E+03 stands for 10^3; curve legends cannot show symbols or subscripts. The sketches should not be understood as technical drawings. Equations in the text are written for clarity with multiplier sign, i.e. a×b (instead of a b). This is not done in the numbered equations.

Literature: There is a general bibliography quoted as [B.1], [B.2], etc. while standards are quoted as [N.1], [N.2], etc. The bulk of the literature is linked to the individual chapters. This eases the search for literature on a specific topic. The roughly 600 quotations provided represent only 1% (order of magnitude) if not less of the relevant literature. This statement applies to all topics treated in this book. The literature quoted was selected with the objectives: (1) to provide the sources of specific data or information; (2) to back up a statement; (3) to refer the reader to more details on the particular investigation or topic; (4) to provide reference to literature in neighboring fields. In spite of these criteria, the selection of the literature quoted is to some extent coincidental.

In order to improve the readability, facts which represent the state of the art are not backed up systematically by quoting literature where they may have been reported. In many cases it would be difficult to ascertain where such facts were published for the first time.

Patents: Possible patents on any devices or design features are not necessarily mentioned. Omission of such mention should not be construed so as to imply that such devices or features are free for use to everybody.

Disclaimer of warranty and exclusion of liabilities: In spite of careful checking text, equations and figures, neither the Springer book company nor the author:

- make any warranty or representation whatsoever, express or implied, (A) with respect of the use of any information, apparatus, method, process or similar item disclosed in this book including merchantability and fitness for practical purpose, or (B) that such use does not infringe or interfere with privately owned rights, including intellectual property, or (C) that this book is suitable to any particular user's circumstances; or
- assume responsibility for any damage or other liability whatsoever (including consequential damage) resulting from the use of any information, apparatus, method, process or similar item disclosed in this book.

In this context it should well be noted that much of the published information on pump hydraulic design is empirical in nature. The information has been gathered from tests on specific pumps. Applying such information to new designs harbors uncertainties which are difficult to asses and to quantify.

Finally it should be noted that the technological focus in the various sectors of the pump industry is quite different. Low-head pumps produced in vast quantities are designed and manufactured to other criteria than engineered high-energy pumps. This implies that the recommendations and design rules given in this book cannot be applied indistinctly to all types of pumps. Notably, issues of standardization and manufacturing are not addressed in this text.

Table of contents

List of tables

List of data tables

Symbols, abbreviations, definitions

Unless otherwise noted all equations are written in consistent units (SI-System). Most symbols are defined in the following. As appropriate, the equation or chapter is quoted where the symbol has been defined or introduced. Vectors in the text and in equations are printed as bold characters. Symbols with local significance only are defined in the text.

The following tables may help the understanding of the physical meaning of various parameters of prime importance:

- Table 0.1 and 0.2: Geometric dimensions of the flow channels, flow angles and velocities
- Table 2.2: Head and net positive suction head (NPSH)
- Tables 3.1 and 3.2: Velocity triangles
- Table 3.4: Model laws and dimensionless parameters

		Chapter or Equation
A	area, cross section	
A	elongation at rupture	Chap. 14
A	amplitude	Chap. 10
A_{1q}	impeller inlet throat area (trapezoidal: $A_{1q} = a_1 \times b_1$)	
A_{2q}	area between vanes at impeller outlet ($A_{2q} = a_2 \times b_2$)	
A_{3q}	diffuser/volute inlet throat area ($A_{3q} = a_3 \times b_3$)	
a	distance between vanes (subscript 1to 6)	Table 0.2
a	sound velocity in a pipe	Eq. (10.17)
a_o	sound velocity in the fluid	Eq. (10.17)
a_L	sound velocity in the casing material	Eq. (T6.1.7)
BEP	best efficiency point	
b	acceleration	
b	width of channel in the meridional section	
b_2	impeller outlet width; if double-entry, per impeller *side*	
b_{2tot} (b_{2ges})	impeller outlet width including shrouds	Eq. (9.6)
b_{ks}	solid-borne noise acceleration	Eq. (10.6)
CNL	cavitation sound pressure	Table 6.1
CV	solid-borne noise as RMS of acceleration	
CV*	dimensionless solid-borne noise acceleration	$CV^* = CV \times d_1/u_1^2$
c	absolute velocity	Chap. 1.1
c	rotor damping coefficient	Eq. (10.7)
c_A	axial thrust reduction coefficient	Eq. (9.4), Table 9.1
c_d	flow velocity in discharge nozzle	
c_{Fe}	concentration of iron ions	Eq. (14.7), Table 14.7
c_{3q}	average velocity in diffuser throat	$c_{3q} = Q_{Le}/(z_{Le} \times A_{3q})$
c_c	cross coupled damping	Eq. (10.7)
c_{eq}	roughness equivalence factor	Eq. (1.36b)
c_f	friction coefficient of a flat plate	Eq. (1.33)
c_p	pressure recovery coefficient	Eqs. (1.11), (1.40), (T9.1.5)
c_p	specific heat at constant pressure	Chap. 13.2
c_{ph}	phase velocity	Chap. 10.7.1
c_s	flow velocity in suction nozzle	

c_s	concentration of solids	Table 14.16
$c_{s,eq}$	equivalent concentration of solids	Table 14.16
c_T	velocity at inlet to suction bell	Eq. (11.15)
c_v	solids volume concentration	Table 13.5
D	damping coefficient	Chap. 10.6.5
D, d	diameter	
D_{fz}	diffusion factor	Table 7.5
DE	drive end	
DR	liquid/gas density ratio $DR \equiv \rho^* = \rho'/\rho''$	Chap. 13.2
D_T	inlet diameter of suction bell	Fig. (11.20)
d_{3q}	equivalent diameter of volute throat	Eq. (T7.7.7)
d_b	arithmetic average of diameters at impeller or diffuser e.g. $d_{1b} = 0.5\ (d_1 + d_{1i})$; defined such that: $A_1 = \pi \times d_{1b} \times b_1$	Table 0.2
d_d	inner diameter of discharge nozzle	
d_m	geometric average of diameters at impeller or diffuser, e.g. $d_{1m} = \sqrt{0.5(d_{1a}^2 + d_{1i}^2)}$	Table 0.2
d_n	hub diameter	
d_D	diameter at shaft seal	Table 9.1
d_s	inner diameter of suction nozzle	
d_s	diameter of solid particles	Table 14.16
E	Young's modulus of elasticity	
E_R	maximum erosion rate (at location of highest metal loss)	Table 6.1
$E_{R,a}$	metal loss rate in mm/a	Tables 14.7 and 14.16
e	vane thickness	Table 0.2
F	force	
F_{ax}	axial force ("axial thrust")	
F_{Dsp}	radial thrust correction factor for double volutes, Fig. 9.18	Table 9.4
F_R	radial force ("radial thrust")	Eq. (9.6), Table 9.4
Fr	Froude number	Chap. 11.7.3
F_r, F_t	radial- and tangential forces on rotor	Eq. (10.8)
F_{cor}	corrosion factor	Table 6.1
F_{Mat}	material factor for cavitation: Table 6.1, for abrasion: Table 14.16	
f	frequency	
f_{EB}	natural frequency at operational speed	Chap. 10.6.5
f_{e1}	natural frequency	Chap. 10.6.2
f_{kr}	critical speed (as frequency)	Chap. 10.6.5
f_L	influence of leakage flow on disk friction	Eq. (T3.6.7), Table 3.6
f_n	frequency of rotation $f_n = n/60$	
f_q	impeller eyes per impeller: single-entry $f_q = 1$; double-entry $f_q = 2$	
f_H	correction factor for head (roughness, viscosity)	Eq. (3.32)
f_Q	correction factor for flow rate (viscosity)	Eq. (3.32)
f_R	roughness influence on disk friction	Eq. (T3.6.6)
f_{RS}	frequency of rotating stall	
f_η	correction factor for efficiency (roughness, viscosity)	Eq. (3.31)
g	acceleration due to gravity ($g = 9.81\ m/s^2$, rounded)	appendix A.4
H	head *per stage*	Tables 2.2, 3.3
H_{Mat}	hardness of material	Table 14.16

H_s	hardness of solid particle	Table 14.16
H_{tot}	total head of a multistage pump	Table 2.2
H_p	static pressure rise in impeller	Eq. (T3.3.8)
h_{tot}	total enthalpy	Eq. (1.4)
h	casing wall thickness (at location of accelerometer)	Table 6.1
h_D	casing cover wall thickness	Table 6.1
I_{ac}	acoustic intensity	Table 6.1
I_{Ref}	reference value for intensity	Table 6.1
i	incidence (i = blade angle minus flow angle)	Table 3.1
J_{sp}	integral over diffuser or volute throat area	Eq. (3.15); (4.13)
k	rotation of fluid in impeller sidewall gap $k = \beta/\omega$	Eq. (9.1), Table 9.1
k_E, k_z	rotation of fluid at inlet to impeller sidewall gap	Fig. 9.1
k	stiffness	Eq. (10.7)
k_c	cross coupled stiffness	Eq. (10.7)
k_n	blockage caused by hub: $k_n = 1 - d_n^2/d_1^2$	
k_R	radial thrust coefficient (steady component)	Eq. (9.6)
$k_{R,D}$	radial thrust coefficient referred to d_2 (steady)	Table 9.4
$k_{R,dyn}$	dynamic (unsteady) radial thrust coefficient	Table 9.4
$k_{R,tot}$	total radial thrust coefficient (steady and unsteady)	Table 9.4
$k_{R,o}$	radial thrust coefficient (steady) for operation at Q = 0	Table 9.4
k_{Ru}	radial thrust coefficient (steady)	Eq. (9.7)
k_{RR}	disk friction coefficient	Table 3.6
L	length	
L_{PA}	A-type sound pressure level	Table 10.4
L_{Dam}	damage length	
L_{cav}	cavity length	
M	torque	
m	difference of impeller and diffuser periodicity	Chap. 10.7.1
m	mass coefficient	Eq. (10.7)
$\dot{m}$	mass flow rate	
m_c	cross coupled mass	Eq. (10.7)
NDE	non drive end	
NPSH	net positive suction head	
$NPSH_A$	net positive suction head available	Table 2.2, Table 6.2
$NPSH_i$	net positive suction head required for cavitation inception	
$NPSH_R$	net positive suction head required according to a specific cavitation criterion	Chap. 6.2.2, 6.2.5, 6.3
$NPSH_x$	net positive suction head required for operation with x-per cent head drop	Chap. 6.2.2
NL	fluid-borne sound pressure as RMS value; $NL^* = 2NL/(\rho \times u_1^2)$	
NL_o	background sound pressure	Chap. 6.5
n	rotational speed (revolutions per minute)	
$n^{(s)}$	rotational speed (revolutions per second)	
n_N	nominal speed	
n_q	specific speed [rpm, m^3/s, m]	Table D2.1, Chap. 3.4, Table 3.4

n_{ss}	suction specific speed [rpm, m^3/s, m]	Chap. 6.2.4, Table 3.4
P	power; without subscript: power at coupling	
P_i	inner power	Table 3.5
P_m	mechanical power losses	Table 3.5
P_u	useful power transferred to fluid $P_u = \rho \times g \times H_{tot} \times Q$	Table 3.5
P_{RR}	disk friction power	Tables 3.6, 3.5
P_{ER}	specific erosion power $P_{ER} = U_R \times E_R$	Table 6.1
P_{er}	disk friction power loss caused by balance device	Table 3.6
P_{s3}	power loss dissipated in inter-stage seal	Tables 3.5, 3.7(1)
PI	pitting index	Eq. (14.8)
p	static pressure	
p	periodicity	Chap. 10.7.1
p_{amb}	ambient pressure at location of pump installation (usually atmospheric pressure)	
p_e	pressure above liquid level in suction reservoir	Table 2.2
p_g	gas pressure (partial pressure)	Appendix A.3
p_i	implosion pressure	Table 6.1
p_v	vapor pressure	
Q	flow rate, volumetric flow	
Q_{La}	flow rate through impeller: $Q_{La} = Q + Q_{sp} + Q_E + Q_h = Q/\eta_v$	
Q_{Le}	flow rate through diffuser: $Q_{Le} = Q + Q_{s3} + Q_E$	
Q_E	flow rate through axial thrust balancing device	
Q_h	flow rate through auxiliaries (mostly zero)	
Q_R	rated flow or nominal flow rate	Chap.15
Q_{sp}	leakage flow rate through seal at impeller inlet	Tables 3.5, 3.7(1)
Q_{s3}	leakage flow rate through inter-stage seal	Tables 3.5, 3.7(1)
q*	flow rate referred to flow rate at best efficiency point:	$q^* \equiv Q/Q_{opt}$
R, r	radius	
R_G	degree of reaction	Chap. 3.2
Re	Reynolds number, channel: $Re = c \times D_h/\nu$; plate or blade: $Re = w \times L/\nu$	
Ro	Rossby number	Chap. 5.2
R_m	tensile strength	
RMS	root mean square	
R	gas constant	Table 13.3
r_{3q}	equivalent radius of volute throat area	Table 7.7
S	submergence	Chap. 11.7.3
S	sound absorbing surface of inlet casing	Table 6.1
SG	specific gravity; $SG \equiv \rho/\rho_{Ref}$ with $\rho_{Ref} = 1000$ kg/m^3	
S_{Str}	Strouhal number	Table 10.13
s	*radial* clearance	Eq. (3.12), Fig. 3.12, Table 3.7(1) and (2)
s_{ax}	axial distance between impeller shrouds and casing	Fig. 9.1
T	temperature	
t	time	
t	pitch:	$t = \pi \times d/z_{La}$ (or z_{Le})
t_{ax}	axial casing part in impeller sidewall gap	Fig. 9.1

U	wetted perimeter (of a pipe or channel)	
U_R	ultimate resilience: $U_R = R_m^2/(2\times E)$	Table 6.1
u	circumferential velocity	$u = \pi\times d\times n/60$
V	volume	
w	relative velocity	
w_{1q}	average velocity in impeller throat area	$w_{1q} = Q_{La}/(z_{La}\times A_{1q})$
x	dimensionless radius $x = r/r_2$	Table 9.1
x	gas (or vapor) mass content; mass concentration of solids	Chap. 13
x_D	mass concentration of dissolved gas	Appendix A.3
x_{ov}	overlap at impeller/diffuser side disks	Fig. 9.1
Y	specific work	$Y = g\times H$
$Y_{sch} \equiv Y_{th}$	specific work done by the impeller blades: $Y_{th} = g\times H_{th}$	Table 3.3
$Y_{th\infty}$	specific work done by the impeller blades with vane congruent flow	
y^+	dimensionless distance from the wall	Table 8.1
Z	real gas factor	Table 13.3
Z_h	hydraulic losses (impeller: Z_{La} diffuser: Z_{Le})	
z	height coordinate	
z_{La}	number of impeller blades	
z_{Le}	number of diffuser vanes (volute: number of cutwaters)	
z_R	number of return vanes	
z_{pp}	number of pumps operating in parallel	
z_{st}	number of stages	
z_{VLe}	number of vanes of pre-rotation control device	

$\alpha \equiv$ GVF	gas content, gas volume fraction, void fraction	Table 13.2
α	angle between direction of circumferential and absolute velocity	
α_k	notch factor	Eq. (T14.1.7)
α_T	total absorption coefficient	Table 6.1
β	angle between relative velocity vector and the negative direction of circumferential velocity	
β	angular velocity of fluid between impeller and casing	Chap. 9.1
β	mass transfer coefficient	Chap. 14.3, Table 14.8
γ	impeller discharge coefficient ("slip factor")	Table 3.2
δ^*	displacement thickness	Eq. (1.18)
Δp^*_d	pressure pulsations (dimensionless)	Eq. (10.1)
Δp_a	amplitude of pressure pulsations	Chap. 10.2.6
Δp_{p-p}	pressure pulsations measured peak-to-peak	Chap. 10.2.6
ε	angle in polar coordinate system	
ε	equivalent sand roughness	Chap. 1.5.2
ε_{sp}	wrap angle of the inner volute (for double volutes)	Table 0.2
ζ	loss coefficient (with subscript La, Le, Sp etc.)	Table 3.8
ζ_a	lift coefficient	Tables 7.1, 7.4
ζ_w	drag coefficient	Table 7.4
η_{vol}, η_v	volumetric efficiency	Eq. (T3.5.9)

η	overall efficiency (at coupling)	Eq. (T3.5.3)
η_i	inner efficiency	Eq. (T3.5.5)
η_h	hydraulic efficiency	Eq. (T3.5.8) and Table 3.8
η_D	diffuser efficiency	Eq. (1.43)
η_{st}	stage efficiency	Eq. (T3.5.7)
θ_u	similarity parameter for cavitation erosion	Table 6.1
ϑ	diffuser opening angle	Eq. (1.42)
κ	exponent of isentropic expansion/compression	Table 13.3(2)
λ	angle between vanes and side disks (impeller or diffuser)	Table 0.1
λ	power coefficient	Table 3.4
λ	wave length	Table 10.12
λ_c, λ_w	coefficient for NPSH calculation	Eq. (6.10)
λ_R	friction coefficient for pipes and channels	Eq. (1.36)
μ	dynamic viscosity: $\mu = \rho \times \nu$	
ν	kinematic viscosity: $\nu = \mu/\rho$	
ν	hub ratio	$\nu = d_n/d_{1a}$
ν_1, ν_2	vibration orders, natural numbers (1, 2, 3, ….)	
ξ	hydraulic vane loading according to [7.2]	Table 7.1
ρ	density	
ρ''	density of gas or saturated vapor	
ρ_{mat}	density of material	
ρ_p	density of casing material	
ρ_s	density of solids suspended in the fluids	Chap. 13.4, 14.5
σ	cavitation coefficient (same subscripts as NPSH)	Table 3.4
σ	mechanical stress	Chap. 14.1
τ	blade blockage factor	Table 0.1
τ	shear stress	
φ	flow coefficient	Table 3.4
φ_{sp}	flow coefficient of impeller sidewall gap	Table 9.1
ψ	head coefficient	Table 3.4
ψ_p	pressure coefficient of static pressure rise in impeller	Table 3.3
Ω	orbit- (vibration-)circular frequency	Chap. 10.6.2
Ω_{limit}	orbit frequency of stability limit	Eq. (10.9)
ω	angular rotor velocity	
ω_E	circular natural frequency	Chap. 10
ω_s	universal specific speed	Table D2.1, Table 3.4

Subscripts, superscripts, abbreviations

Sequence of calculations: in the pumping mode the fluid flows from station 1 to 6, in the turbine mode from 6 to 1:

1	impeller blade leading edge (low pressure)	
2	impeller blade trailing edge (high pressure)	
3	diffuser vane leading edge or volute cutwater	
4	diffuser vane trailing edge	
5	return vane leading edge	
6	return vane trailing edge	
A	plant	
a	plant, executed pump, prototype	
al	allowable	
ax	axial	
a,m,i	outer, mean, inner streamline	
B	blade angle (impeller, diffuser, volute cutwater)	
cor	corrosion	
DE	drive end (coupling end of a pump shaft)	
Ds (FS)	front shroud	
d	discharge nozzle	
ER	erosion	
eff	effective	
FS	front shroud	
GVF	gas volume fraction, void fraction	Table 13.2
h	hydraulic	
L	run-away in turbine mode (M = 0)	Chap. 12
La	impeller	
Le	diffuser	
LE	leading edge	
M	model	
m	meridional component	
max	maximum	
min	minimum	
mix	two-phase mixture	
NDE	non-drive end (of a pump shaft)	
o	shut-off operation (Q = 0)	
opt	operation at maximum (best) efficiency (BEP)	
P	pumping mode	Chap. 12
PS (DS)	pressure surface (pressure side)	
pol	polytropic	Chap. 13.2
q	average velocity calculated from continuity (to be distinguished from velocity vector)	
RB	onset of recirculation	
Rec (Rez)	recirculation	
Ref	reference value	
RR	disk friction	Chap. 3.6.1, Table 3.6
RS	rear shroud or hub	
r	radial	
s	inlet or suction nozzle	

s	solid particle	Chap. 13.4
sch	blade or vane	
SF	shockless flow (zero incidence)	Eq. (T3.1.10)
Sp	volute	
sp	annular seal, leakage flow	
SPL	single-phase liquid	
SS	suction surface (suction side)	
st	stage	
stat	static	
T	turbine mode	Chap. 12
TE	trailing edge	
TP	two-phase	
Ts (RS)	rear shroud or hub	
th	theoretical flow conditions (flow without losses)	
tot	total (total pressure = static pressure + stagnation pressure)	
u	circumferential component	
v	loss	
v	viscous fluid	Chap. 13
w	water	Chap. 13.1
w	resistance curve in turbine mode locked rotor (n = 0)	Chap. 12
zul (al)	allowable	

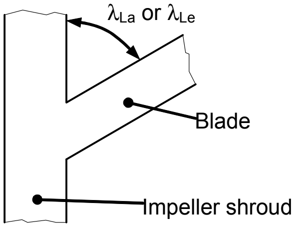
The following are superscripts:

'	with blade blockage	Tables 0.1, 3.1
*	dimensionless quantity: all dimensions are referred to d_2 e.g. $b_2^* = b_2/d_2$, velocities are referred to u_2, e.g. $w_1^* = w_1/u_2$	
'	liquid phase	Chap. 6 & 13
"	gaseous phase	Chap. 6 & 13

Table 0.1 Dimensions and flow parameters

	Location, main dimensions	Blade blockage	Flow parameters	Vane angles
Impeller: z_{La}	Inlet: d_{1a}, d_{1m}, d_{1i}, d_n, a_1, e_1	without	u_{1a}, u_{1m}, u_{1i}, c_{1m}, c_{1u}, c_1, w_1, α_1, β_1	$\beta_{1B,a}$ β_{1B} $\beta_{1B,i}$
		$\tau_1 = \frac{1}{1 - \frac{z_{La} e_1}{\pi\ d_1\ \sin\beta_{1B} \sin\lambda_{La}}}$	c_{1m}', c_{1u}, w_1', c_1', α_1', β_1' $w_{1q} = Q_{La}/(z_{La}\ A_{1q})$	
	Outlet: d_{2a}, d_{2m}, d_{2i}, b_2, a_2, e_2, e	$\tau_2 = \frac{1}{1 - \frac{z_{La} e_2}{\pi d_2 \sin\beta_{2B} \sin\lambda_{La}}}$	c_{2m}', c_{2u}, c_2', w_{2u}, w_2', α_2', β_2'	$\beta_{2B,a}$ β_{2B} $\beta_{2B,i}$
		without	u_{2a}, u_{2m}, u_{2i}, c_{2m}, c_{2u} c_2, w_{2u}, w_2, α_2, β_2	
Diffuser or volute: z_{Le}	Inlet: d_3, b_3, a_3, e_3 $A_{3q} = a_3\ b_3$	without	c_{3m}, c_{3u}, c_3, α_3	$\alpha_{3B,a}$ α_{3B} $\alpha_{3B,i}$
		$\tau_3 = \frac{1}{1 - \frac{z_{Le}\ e_3}{\pi d_3 \sin\alpha_{3B} \sin\lambda_{Le}}}$	c_{3m}', c_{3u}, c_3', α_3' $c_{3q} = Q_{Le}/(z_{Le}\ A_{3q})$	
	Outlet: d_4, b_4, a_4, e_4, $A_4 = a_4\ b_4$	$c_4 = \frac{Q_{Le}}{z_{Le}\ b_4\ a_4}$		$\alpha_{4B,a}$ α_{4B} $\alpha_{4B,i}$
Return vanes: z_R	Inlet: d_5, b_5, a_5, e_5	without	c_{5m}, c_{5u}, c_5, α_5	$\alpha_{5B,a}$ α_{5B} $\alpha_{5B,i}$
		$\tau_5 = \frac{1}{1 - \frac{z_R \cdot e_5}{\pi d_5\ \sin\alpha_{5B}}}$	c_{5m}', c_{5u}, c_5', α_5'	
	Outlet: d_6, b_6, a_6, e_6	$\tau_6 = \frac{1}{1 - \frac{z_R e_6}{\pi d_6 \sin\alpha_{6B}}}$	c_{6m}', c_{6u}, c_6', α_6'	$\alpha_{6B,a}$ α_{6B} $\alpha_{6B,i}$
		without	c_{6m}, c_{6u}, c_6, α_6	

Note:
All flow parameters can be supplemented by subscripts a, m or i in order to define the streamline e.g. $c_{1m,a}$, β_{1a}, β_{1i}
Without special subscript: $u_1 \equiv u_{1a}$ and $d_1 \equiv d_{1a}$ as well as $d_2 \equiv d_{2a}$, if $d_{2a} = d_{2i}$
The meridional velocity components are equal in relative and absolute system: $w_m = c_m$
Circumferential velocity components c_u and w_u are not influenced by blade blockage.



Influence of blade inclination on blade blockage (twisted blades)

Table 0.2 (1) Geometric dimensions