

# Contents

<b>1</b>	<b>Fluid Dynamic Principles</b>	<b>1</b>
1.1	Flow in the Absolute and Relative Reference Frame	1
1.2	Conservation Equations	2
1.2.1	Conservation of Mass	2
1.2.2	Conservation of Energy	3
1.2.3	Conservation of Momentum	5
1.3	Boundary Layers, Boundary Layer Control	7
1.4	Flow on Curved Streamlines	11
1.4.1	Equilibrium of Forces	11
1.4.2	Forced and Free Vortices	15
1.4.3	Flow in Curved Channels	17
1.5	Pressure Losses	18
1.5.1	Friction Losses (Skin Friction)	19
1.5.2	Influence of Roughness on Friction Losses	21
1.5.3	Losses Due to Vortex Dissipation (Form Drag)	25
1.6	Diffusers	27
1.7	Submerged Jets	32
1.8	Equalization of Non-uniform Velocity Profiles	33
1.9	Flow Distribution in Parallel Channels, Piping Networks	36
	References	41
<b>2</b>	<b>Pump Types and Performance Data</b>	<b>43</b>
2.1	Basic Principles and Components	43
2.2	Performance Data	47
2.2.1	Specific Work, Head	47
2.2.2	Net Positive Suction Head, NPSH	48
2.2.3	Power and Efficiency	50
2.2.4	Pump Characteristics	51
2.3	Pump Types and their Applications	51
2.3.1	Overview	51
2.3.2	Classification of Pumps and Applications	53

2.3.3	Pump Types .....	55
2.3.4	Special Pump Types .....	72
References	.....	77
<b>3</b>	<b>Pump Hydraulics and Physical Concepts .....</b>	<b>79</b>
3.1	One-dimensional Calculation with Velocity Triangles .....	79
3.2	Energy Transfer in the Impeller, Specific Work and Head .....	83
3.3	Flow Deflection Caused by the Blades. Slip Factor .....	85
3.4	Dimensionless Coefficients, Similarity Laws and Specific Speed ...	90
3.5	Power Balance and Efficiencies .....	93
3.6	Calculation of Secondary Losses .....	95
3.6.1	Disk Friction Losses .....	95
3.6.2	Leakage Losses Through Annular Seals .....	99
3.6.3	Power Loss Caused by the Inter-Stage Seal .....	108
3.6.4	Leakage Loss of Radial or Diagonal Seals .....	108
3.6.5	Leakage Losses in Open Impellers .....	109
3.6.6	Mechanical Losses .....	111
3.7	Basic Hydraulic Calculations of Collectors .....	111
3.8	Hydraulic Losses .....	117
3.9	Statistical Data of Pressure Coefficients, Efficiencies and Losses ...	123
3.10	Influence of Roughness and Reynolds Number .....	132
3.10.1	Overview .....	132
3.10.2	Efficiency Scaling .....	133
3.10.3	Calculation of the Efficiency from Loss Analysis .....	135
3.11	Minimization of Losses .....	140
3.12	Compendium of Equations for Hydraulic Calculations .....	141
References	.....	156
<b>4</b>	<b>Performance Characteristics .....</b>	<b>159</b>
4.1	Head-Capacity Characteristic and Power Consumption .....	160
4.1.1	Theoretical Head Curve (Without Losses) .....	160
4.1.2	Real Characteristics With Losses .....	162
4.1.3	Component Characteristics .....	165
4.1.4	Head and Power at Operation Against Closed Discharge Valve .....	173
4.1.5	Influence of Pump Size and Speed .....	176
4.1.6	Influence of Specific Speed on the Shape of the Characteristics .....	177
4.2	Best Efficiency Point .....	177
4.3	Prediction of Pump Characteristics .....	182
4.4	Range Charts .....	183
4.5	Modification of the Pump Characteristics .....	186
4.5.1	Impeller Trimming .....	186
4.5.2	Under-Filing And Over-Filing of the Blades at the Trailing Edge .....	194
4.5.3	Collector Modifications .....	195

4.6	Analysis of Performance Deviations .....	195
4.7	Calculation of Modifications of the Pump Characteristics .....	199
	References .....	203
<b>5</b>	<b>Partload Operation, Impact of 3-D Flow Phenomena Performance ...</b>	<b>205</b>
5.1	Basic Considerations .....	205
5.2	The Flow Through the Impeller .....	209
5.2.1	Overview .....	209
5.2.2	Physical Mechanisms .....	211
5.2.3	The Combined Effect of Different Mechanisms .....	217
5.2.4	Recirculation at the Impeller Inlet .....	219
5.2.5	Flow at the Impeller Outlet .....	225
5.2.6	Experimental Detection of the Onset of Recirculation .....	227
5.3	The Flow in the Collector .....	228
5.3.1	Flow Separation in the Diffuser .....	228
5.3.2	Pressure Recovery in the Diffuser .....	232
5.3.3	Influence of Approach Flow on Pressure Recovery and Stall .....	233
5.3.4	Flow in the Volute Casing .....	234
5.3.5	Flow in Annular Casings and Vaneless Diffusers .....	235
5.4	The Effects of Flow Recirculation .....	236
5.4.1	Effects of Flow Recirculation at the Impeller Inlet .....	236
5.4.2	Effect of Flow Recirculation at the Impeller Outlet .....	241
5.4.3	Effect of Outlet Recirculation on the Flow in the Impeller Sidewall Gaps and on Axial Thrust .....	248
5.4.4	Damaging Effects of Partload Recirculation .....	251
5.5	Influence of Flow Separation and Recirculation on the Q-H-Curve .....	252
5.5.1	Types of Q-H-Curve Instability .....	252
5.5.2	Saddle-Type Instabilities .....	253
5.5.3	Type F Instabilities .....	261
5.6	Means to Influence the Shape of The Q-H-Curve .....	261
5.6.1	Introduction .....	261
5.6.2	Influencing the Onset of Recirculation at the Impeller Inlet .....	262
5.6.3	Influencing the Onset of Recirculation at the Impeller Outlet .....	265
5.6.4	Eliminating a Type F Instability .....	266
5.6.5	Influencing the Saddle-Type Instability of Radial Impellers with $n_q < 50$ .....	267
5.6.6	Influencing the Saddle-Type Instability of Radial Impellers with $n_q > 50$ .....	269
5.6.7	Influencing the Instability of Semi-Axial and Axial Impellers .....	270
5.6.8	Reduction of Head and Power at Shut-Off .....	271
5.7	Flow Phenomena in Open Axial Impellers .....	272

5.8	Flow Instabilities in Double-Entry Impellers and Double Volutes ...	280
	References .....	283
<b>6</b>	<b>Suction Capability and Cavitation .....</b>	<b>287</b>
6.1	Cavitation Physics .....	287
6.1.1	Growth and Implosion of Vapor Bubbles in a Flowing Liquid .....	287
6.1.2	Bubble Dynamics .....	289
6.2	Cavitation in Impeller or Diffuser .....	292
6.2.1	Pressure Distribution and Cavity Length .....	292
6.2.2	Required NPSH, Extent of Cavitation, Cavitation Criteria ...	294
6.2.3	Scaling Laws for Cavitating Flows .....	296
6.2.4	The Suction Specific Speed .....	299
6.2.5	Experimental Determination of the Required $NPSH_R$ .....	302
6.2.6	Cavitation in Annular Seals .....	311
6.3	Determination of the Required NPSH .....	312
6.3.1	Parameters Influencing $NPSH_R$ .....	312
6.3.2	Calculation of the $NPSH_R$ .....	315
6.3.3	Estimation of the $NPSH_3$ as Function of the Flow Rate .....	319
6.4	Influence of the Fluid Properties .....	323
6.4.1	Thermodynamic Effects .....	323
6.4.2	Non-Condensable Gases .....	326
6.4.3	Nuclei Content and Tensile Stresses in the Liquid .....	327
6.5	Cavitation-Induced Noise and Vibrations .....	329
6.5.1	Excitation Mechanisms .....	329
6.5.2	Cavitation Noise Measurements for Quantifying the Hydrodynamic Cavitation Intensity .....	330
6.5.3	Frequency Characteristics of Cavitation Noise .....	333
6.6	Cavitation Erosion .....	335
6.6.1	Testing Methods .....	335
6.6.2	Cavitation Resistance .....	338
6.6.3	Prediction of Cavitation Damage Based on Cavity Length ...	340
6.6.4	Prediction of Cavitation Damage Based on Cavitation Noise .....	345
6.6.5	Solid-Borne Noise Measurements for Cavitation Diagnosis .....	346
6.6.6	Paint Erosion Tests to Determine the Location of Bubble Implosion .....	348
6.6.7	Onset of Erosion and Behavior of Material Subject to Different Hydrodynamic Cavitation Intensities .....	349
6.6.8	Summarizing Assessment .....	353
6.7	Selection of the Inlet Pressure in a Plant .....	355
6.8	Cavitation Damage: Analysis and Remedies .....	358
6.8.1	Record Damage and Operation Parameters .....	358
6.8.2	Forms of Cavitation and Typical Cavitation Damage Patterns .....	359

6.8.3	Reduction or Elimination of Cavitation Damage .....	369
6.9	Insufficient Suction Capacity: Analysis and Remedies .....	371
	References .....	372
<b>7</b>	<b>Design of the Hydraulic Components .....</b>	<b>375</b>
7.1	Methods and Boundary Conditions .....	375
7.1.1	Methods for the Development of Hydraulic Components ...	375
7.1.2	The Hydraulic Specification .....	376
7.1.3	Calculation Models .....	378
7.2	Radial Impellers .....	380
7.2.1	Determination of Main Dimensions .....	380
7.2.2	Impeller Design .....	389
7.2.3	Criteria for Shaping the Blades .....	396
7.2.4	Criteria for Suction Impeller Design .....	397
7.2.5	Exploiting Three-Dimensional Effects in Design .....	400
7.3	Radial impellers for Small Specific Speeds .....	401
7.3.1	Two-Dimensional Blades .....	401
7.3.2	Pumping Disks with Channels of Circular Section .....	402
7.3.3	Impellers with Straight Radial Blades .....	405
7.3.4	Double-Acting Impeller with Straight Radial Blades .....	406
7.4	Radial Impellers for Non-Clogging Pumps .....	407
7.5	Semi-Axial Impellers .....	415
7.6	Axial Impellers and Diffusers .....	420
7.6.1	Features .....	420
7.6.2	Calculation and Selection of Main Dimensions .....	421
7.6.3	Basic Properties of Airfoils .....	426
7.6.4	Blade Design .....	432
7.6.5	Profile Selection .....	440
7.6.6	Design of Axial Diffusers .....	442
7.7	Inducers .....	444
7.7.1	Calculation of Inducer Parameters .....	445
7.7.2	Design and Shaping of an Inducer .....	450
7.7.3	Matching the Inducer to the Impeller .....	451
7.7.4	Recommendations for Inducer Application .....	452
7.8	Volute Casings .....	454
7.8.1	Calculation and Selection of Main Dimensions .....	454
7.8.2	Design and Shaping of Volute Casings .....	460
7.8.3	Influence of the Volute Shape on Hydraulic Performance ...	464
7.9	Radial Diffusers with or Without Return Channels .....	467
7.9.1	Calculation and Selection of Main Dimensions .....	467
7.9.2	Design and Shaping of Radial Diffusers .....	473
7.10	Semi-Axial Diffusers .....	474
7.11	Volutes Combined with a Diffuser or Stay Vanes .....	477
7.12	Annular Casings and Vaneless Diffusers .....	477
7.13	Inlet Casings for Between-Bearing Pumps .....	478

7.14	Analytical Method for Impeller Design .....	483
7.14.1	Motivation, Scope and Objectives .....	483
7.14.2	Meridional Section .....	484
7.14.3	Blade Design .....	490
7.14.4	Procedure for Developing a Design Systematic .....	490
7.14.5	Some Results .....	494
	References .....	494
<b>8</b>	<b>Numerical Flow Calculations .....</b>	<b>499</b>
8.1	Overview .....	499
8.2	Quasi-3D-Procedures and 3D-Euler-Calculations .....	501
8.2.1	Quasi-3D- Procedures .....	501
8.2.2	Three-Dimensional Euler-Procedures .....	502
8.3	Basics of Navier-Stokes Calculations .....	503
8.3.1	The Navier-Stokes Equations .....	503
8.3.2	Turbulence Models .....	504
8.3.3	Treatment of Near-Wall Flows .....	508
8.3.4	Grid Generation .....	511
8.3.5	Numerical Procedures and Control Parameters .....	514
8.3.6	Boundary Conditions .....	516
8.3.7	Initial Conditions .....	518
8.3.8	Possibilities of 3D-Navier-Stokes-Calculations .....	519
8.4	Averaging and Post-Processing .....	522
8.5	Impeller Calculations .....	532
8.5.1	Global Performance at Best Efficiency Flow Rate .....	532
8.5.2	Velocity Profiles .....	535
8.5.3	Influencing Parameters .....	536
8.5.4	Sample Calculation .....	536
8.6	Calculation of Collectors and Stages .....	539
8.6.1	Separate Calculation of the Collector .....	539
8.6.2	Steady Calculations of Stages or Complete Pumps .....	541
8.6.3	Unsteady Calculations .....	542
8.7	Two-Phase and Cavitating Flows .....	543
8.8	Calculation Strategy, Uncertainties, Quality Issues .....	548
8.8.1	Uncertainties, Sources and Reduction of Errors .....	548
8.8.2	CFD Quality Assurance .....	550
8.8.3	Comparison Between Calculation and Experiment .....	561
8.9	Criteria for Assessment of Numerical Calculations .....	563
8.9.1	General Remarks .....	563
8.9.2	Consistence and Plausibility of the Calculation .....	564
8.9.3	Will the Specified Performance be Reached? .....	564
8.9.4	Maximization of the Hydraulic Efficiency .....	565

8.9.5	Stability of the Head-Capacity Curve .....	567
8.9.6	Unsteady Forces .....	568
8.10	Fundamental Considerations on CFD-Calculations .....	568
	References .....	571
<b>9</b>	<b>Hydraulic Forces .....</b>	<b>575</b>
9.1	Flow Phenomena in the Impeller Sidewall Gaps .....	575
9.2	Axial Forces .....	592
9.2.1	General Procedure for Calculating Axial Forces .....	592
9.2.2	Single-Stage Pumps with Single-Entry Overhung Impellers .....	595
9.2.3	Multistage Pumps .....	596
9.2.4	Double-Entry Impellers .....	604
9.2.5	Semi-Axial Impellers .....	605
9.2.6	Axial Pumps .....	606
9.2.7	Expeller Vanes .....	606
9.2.8	Semi-Open and Open Impellers .....	609
9.2.9	Unsteady Axial Thrust .....	609
9.2.10	Axial Thrust Calculation Overview .....	610
9.3	Radial Forces .....	613
9.3.1	Definition and Scope .....	613
9.3.2	Measurement of Radial Forces .....	615
9.3.3	Pumps with Single Volute .....	616
9.3.4	Pumps with Double Volute .....	622
9.3.5	Pumps with Annular Casings .....	624
9.3.6	Diffuser Pumps .....	624
9.3.7	Radial Forces Created by Non-Uniform Approach Flows ...	625
9.3.8	Axial Pumps .....	626
9.3.9	Radial Forces in Pumps with Single-Channel Impellers .....	627
9.3.10	Radial Thrust Balancing .....	640
9.3.11	Radial Thrust Prediction .....	641
	References .....	646
<b>10</b>	<b>Noise and Vibrations .....</b>	<b>649</b>
10.1	Unsteady Flow at the Impeller Outlet .....	650
10.2	Pressure Pulsations .....	653
10.2.1	Generation of Pressure Pulsations .....	654
10.2.2	Noise Generation in a Fluid .....	654
10.2.3	Influence Parameters of the Pump .....	655
10.2.4	Influence of the System .....	658
10.2.5	Scaling Laws .....	660
10.2.6	Measurement and Evaluation of Pressure Pulsations .....	661
10.2.7	Pressure Pulsations of Pumps in Operation .....	663
10.2.8	Damaging Effects of Pressure Pulsations .....	663
10.2.9	Design Guidelines .....	666

10.3	Component Loading by Transient Flow Conditions .....	668
10.4	Radiation of Noise .....	669
10.4.1	Solid-Borne Noise .....	669
10.4.2	Air-Borne Noise .....	671
10.5	Overview of Mechanical Vibrations of Centrifugal Pumps .....	674
10.6	Rotor Dynamics .....	676
10.6.1	Overview .....	676
10.6.2	Forces in Annular Seals .....	677
10.6.3	Hydraulic Impeller Interaction .....	684
10.6.4	Bearing Reaction Forces .....	686
10.6.5	Eigen Values and Critical Speeds .....	687
10.6.6	Rotor Instabilities .....	690
10.7	Hydraulic Excitation of Vibrations .....	693
10.7.1	Interaction Between Flows Through Rotor and Stator (RSI) .....	693
10.7.2	Rotating Stall .....	705
10.7.3	Various Hydraulic Excitation Mechanisms .....	708
10.8	Guidelines for the Design of Pumps with Low Sensitivity to Vibrations .....	720
10.9	Allowable Vibrations .....	723
10.10	General Vibration Diagnostics .....	726
10.10.1	Overview .....	726
10.10.2	Vibration Measurements .....	727
10.10.3	Vibration Diagnostics .....	729
10.11	Bearing Housing Vibrations: Mechanism, Diagnostics, Remedies .....	737
10.11.1	Hydraulic Excitation Mechanisms .....	738
10.11.2	Mechanical Reaction to Hydraulic Excitation .....	742
10.11.3	Hydraulic Versus Mechanical Remedies .....	745
10.11.4	Bearing Housing Vibration Diagnostics .....	746
10.12	Hydraulic and Acoustic Excitation of Pipe Vibrations .....	757
10.12.1	Excitation of Pipe Vibrations by Pumps .....	758
10.12.2	Excitation of Pipe Vibrations by Components .....	760
10.12.3	Acoustic Resonances in Pipelines .....	761
10.12.4	Hydraulic Excitation by Vortex Streets .....	766
10.12.5	Coupling of Flow Phenomena with Acoustics .....	769
10.12.6	Pipe Vibration Mechanisms .....	775
10.13	Torsional Vibrations .....	779
	References .....	783
<b>11</b>	<b>Operation of Centrifugal Pumps .....</b>	<b>787</b>
11.1	System Characteristics, Operation in Parallel or in Series .....	787
11.2	Pump Control .....	792
11.3	Static and Dynamic Stability .....	799



11.4	Start-Up and Shut-Down .....	801
11.5	Power Failure, Water Hammer .....	806
11.6	Allowable Operation Range .....	807
11.7	The Approach Flow to the Pump .....	811
11.7.1	Suction Piping Layout .....	811
11.7.2	Transient Suction Pressure Decay .....	813
11.7.3	Pump Intakes and Suction from Tanks with Free Liquid Level .....	819
11.7.4	Can Pumps .....	834
11.8	Discharge Piping .....	835
	References .....	839
<b>12</b>	<b>Turbine Operation, General Characteristics .....</b>	<b>841</b>
12.1	Reverse Running Centrifugal Pumps Used as Turbines .....	841
12.1.1	Theoretical and Actual Characteristics .....	841
12.1.2	Runaway and Resistance Characteristics .....	847
12.1.3	Estimation of Turbine Characteristics from Statistical Correlations .....	849
12.1.4	Estimation of Turbine Characteristics from Loss Models .....	853
12.1.5	Behavior of Turbines in Plants .....	856
12.2	General Characteristics .....	861
	References .....	868
<b>13</b>	<b>Influence of the Medium on Performance .....</b>	<b>869</b>
13.1	Pumping Highly Viscous Fluids .....	869
13.1.1	Effect of Viscosity on Losses and Performance Characteristics .....	869
13.1.2	Estimation of Viscous Performance from the Characteristics Measured with Water .....	881
13.1.3	Influence of Viscosity on the Suction Capacity .....	887
13.1.4	Start-up of Pumps in Viscous Service .....	888
13.1.5	Viscous Pumping Applications- Recommendations and Comments .....	889
13.2	Pumping of Gas-Liquid Mixtures .....	890
13.2.1	Two-phase Flow Patterns in Straight Pipe Flow .....	890
13.2.2	Two-phase Flow in Pumps. Physical Mechanisms .....	894
13.2.3	Calculation of Two-phase Pump Performance .....	903
13.2.4	Radial Pumps Operating with Two-phase Flow .....	910
13.2.5	Helico-axial Multiphase Pumps .....	915
13.2.6	System Curves .....	919
13.2.7	Slugs and Gas Pockets .....	921
13.2.8	Free Gas, Dissolved Gas and NPSH .....	922

13.3	Expansion of Two-phase Mixtures in Turbines .....	924
13.3.1	Calculation of the Work Transfer .....	924
13.3.2	Prediction of Turbine Characteristics for Two-phase Flow .....	926
13.4	Hydraulic Transport of Solids .....	929
13.5	Non-Newtonian Liquids .....	937
	References .....	940
<b>14</b>	<b>Selection of Materials Exposed to High Flow Velocities .....</b>	<b>943</b>
14.1	Impeller or Diffuser Fatigue Fractures .....	944
14.2	Corrosion .....	956
14.2.1	Corrosion Fundamentals .....	956
14.2.2	Corrosion Mechanisms .....	957
14.2.3	Corrosion in Fresh Water, Cooling Water, Sewage .....	963
14.2.4	Corrosion in Sea Water and Produced Water .....	966
14.3	Erosion Corrosion in Demineralized Water .....	971
14.4	Material Selection and Allowable Flow Velocities .....	980
14.4.1	Definition of Frequently Encountered Fluids .....	980
14.4.2	Metallic Pump Materials .....	982
14.4.3	Impellers, Diffusers and Casings .....	989
14.4.4	Wear Ring Materials .....	1000
14.4.5	Shaft Materials .....	1003
14.4.6	Materials for Feed Water and Condensate Pumps .....	1004
14.4.7	Materials for FGD-Pumps .....	1005
14.4.8	Composite Materials .....	1006
14.5	Hydro-abrasive Wear .....	1008
14.5.1	Influence Parameters .....	1008
14.5.2	Quantitative Estimation of Hydro-Abrasive Wear .....	1011
14.5.3	Material Behavior and Influence of Solids Properties .....	1016
14.5.4	Material Selection .....	1021
14.5.5	Abrasive Wear in Slurry Pumps .....	1022
14.5.6	Erosion Patterns and Flow Mechanisms .....	1024
	References .....	1030
<b>15</b>	<b>Pump Selection and Quality Considerations .....</b>	<b>1035</b>
15.1	The Pump Specification .....	1036
15.2	Determination of Pump Type and Size .....	1038
15.3	Technical Quality Criteria .....	1044
15.3.1	Hydraulic Criteria .....	1044
15.3.2	Manufacturing Quality .....	1048
15.4	High-Energy Pumps .....	1053
	References .....	1057

<b>16 Pump Testing</b> .....	1059
16.1 Types of Tests and Measurements to be Taken .....	1059
16.2 Test Loop Configurations .....	1061
16.2.1 Types and Layout of Closed Test Loops .....	1063
16.2.2 Closed Test Loop with Pressurizer .....	1063
16.2.3 Semi-Open Test Loop .....	1068
16.2.4 Closed Test Loop with Flow Through Tank with Free Water Level .....	1069
16.2.5 Open Test Loops .....	1070
16.3 Instrumentation .....	1072
16.3.1 Pressure Measurement .....	1073
16.3.2 Flow Rate Measurement .....	1073
16.3.3 Power, Torque and Efficiency Measurement .....	1078
16.4 Test Preparation and Test Procedures .....	1079
16.4.1 Test Preparation .....	1079
16.4.2 Procedure for Performance Test .....	1080
16.4.3 Procedures for Cavitation Testing .....	1080
16.5 Test Evaluation and Accuracy .....	1081
16.6 Potential Testing Problems and Remedies .....	1083
References .....	1083
<b>17 Appendices</b> .....	1085
17.1 Units and Unit Conversion .....	1085
17.2 Properties of Saturated Water .....	1087
17.3 Solution of Gases in Water .....	1090
17.4 Physical Constants .....	1093
17.4.1 Atmospheric Pressure .....	1093
17.4.2 Acceleration due to Gravity .....	1093
17.5 Sound Velocity in Liquids .....	1093
17.6 Mechanical Vibrations—Basic Notions .....	1094
17.7 Hydraulic Specification .....	1104
References .....	1109
<b>Bibliography</b> .....	1111
<b>Index</b> .....	1113