

# Table of contents

<b>1 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.....	4
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 .....	14
1.4.3 Flow in curved channels .....	16
1.5 Pressure losses .....	18
1.5.1 Friction losses (skin friction) .....	18
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 .....	31
1.8 Equalization of non-uniform velocity profiles .....	33
1.9 Flow distribution in parallel channels, piping networks.....	34
<b>2 Pump types and performance data.....</b>	<b>39</b>
2.1 Basic principles and components.....	39
2.2 Performance data .....	43
2.2.1 Specific work, head.....	43
2.2.2 Net positive suction head, NPSH.....	45
2.2.3 Power and efficiency.....	46
2.2.4 Pump characteristics.....	46
2.3 Pump types and their applications .....	47
2.3.1 Overview.....	47
2.3.2 Classification of pumps and applications.....	49
2.3.3 Pump types .....	52
2.3.4 Special pump types .....	64
<b>3 Pump hydraulics and physical concepts .....</b>	<b>69</b>
3.1 One-dimensional calculation with velocity triangles.....	69

---

3.2 Energy transfer in the impeller, specific work and head .....	72
3.3 Flow deflection caused by the blades. Slip factor.....	75
3.4 Dimensionless coefficients, similarity laws and specific speed.....	80
3.5 Power balance and efficiencies.....	83
3.6 Calculation of secondary losses.....	85
3.6.1 Disk friction losses .....	85
3.6.2 Leakage losses through annular seals.....	90
3.6.3 Power loss caused by the inter-stage seal.....	98
3.6.4 Leakage loss of radial or diagonal seals.....	98
3.6.5 Leakage losses in open impellers .....	99
3.6.6 Mechanical losses.....	101
3.7 Basic hydraulic calculations of collectors.....	101
3.8 Hydraulic losses.....	107
3.9 Statistical data of pressure coefficients, efficiencies and losses .....	112
3.10 Influence of roughness and Reynolds number.....	120
3.10.1 Overview .....	120
3.10.2 Efficiency scaling .....	121
3.10.3 Calculation of the efficiency from loss analysis.....	123
3.11 Minimization of losses.....	129
3.12 Compendium of equations for hydraulic calculations .....	130
<b>4 Performance characteristics .....</b>	<b>145</b>
4.1 Head-capacity characteristic and power consumption.....	145
4.1.1 Theoretical head curve (without losses).....	145
4.1.2 Real characteristics with losses .....	148
4.1.3 Component characteristics .....	151
4.1.4 Head and power at operation against closed discharge valve .....	157
4.1.5 Influence of pump size and speed .....	160
4.1.6 Influence of specific speed on the shape of the characteristics .....	160
4.2 Best efficiency point .....	161
4.3 Prediction of pump characteristics.....	166
4.4 Range charts .....	167
4.5 Modification of the pump characteristics .....	169
4.5.1 Impeller trimming.....	170
4.5.2 Under-filing and over-filing of the blades at the trailing edge .....	177
4.5.3 Collector modifications .....	178
4.6 Analysis of performance deviations .....	179
4.7 Calculation of modifications of the pump characteristics.....	182
<b>5 Partload operation, impact of 3-D flow phenomena on performance .....</b>	<b>187</b>
5.1 Basic considerations .....	187
5.2 The flow through the impeller .....	190
5.2.1 Overview .....	190
5.2.2 Physical mechanisms.....	192
5.2.3 The combined effect of different mechanisms .....	198

5.2.4 Recirculation at the impeller inlet .....	200
5.2.5 Flow at the impeller outlet .....	206
5.2.6 Experimental detection of the onset of recirculation.....	207
5.3 The flow in the collector.....	209
5.3.1 Flow separation in the diffuser.....	209
5.3.2 Pressure recovery in the diffuser.....	211
5.3.3 Influence of approach flow on pressure recovery and stall.....	213
5.3.4 Flow in the volute casing .....	214
5.3.5 Flow in annular casings and vaneless diffusers .....	215
5.4 The effects of flow recirculation .....	216
5.4.1 Effects of flow recirculation at the impeller inlet.....	216
5.4.2 Effect of flow recirculation at the impeller outlet .....	220
5.4.3 Effect of outlet recirculation on the flow in the impeller sidewall gaps and on axial thrust.....	226
5.4.4 Damaging effects of partload recirculation.....	229
5.5 Influence of flow separation and recirculation on the Q-H-curve .....	230
5.5.1 Types of Q-H-curve instability .....	230
5.5.2 Saddle-type instabilities .....	231
5.5.3 Type F instabilities .....	238
5.6 Means to influence the shape of the Q-H-curve .....	239
5.6.1 Introduction.....	239
5.6.2 Influencing the onset of recirculation at the impeller inlet .....	240
5.6.3 Influencing the onset of recirculation at the impeller outlet .....	240
5.6.4 Eliminating a type F instability .....	241
5.6.5 Influencing the saddle-type instability of impellers with $n_q < 50$ ....	242
5.6.6 Influencing the saddle-type instability of impellers with $n_q > 50$ ....	244
5.6.7 Influencing the instability of semi-axial and axial impellers .....	244
5.6.8 Reduction of head and power at shut-off .....	248
5.7 Flow phenomena in open axial impellers .....	249
<b>6 Suction capability and cavitation.....</b>	<b>257</b>
6.1 Cavitation physics.....	257
6.1.1 Growth and implosion of vapor bubbles in a flowing liquid .....	257
6.1.2 Bubble dynamics.....	259
6.2 Cavitation in impeller or diffuser .....	262
6.2.1 Pressure distribution and cavity length .....	262
6.2.2 Required NPSH, extent of cavitation, cavitation criteria .....	264
6.2.3 Scaling laws for cavitating flows .....	265
6.2.4 The suction specific speed .....	269
6.2.5 Experimental determination of the required $NPSH_R$ .....	271
6.2.6 Cavitation in annular seals .....	281
6.3 Determination of the required NPSH .....	281
6.3.1 Parameters influencing $NPSH_R$ .....	281
6.3.2 Calculation of the $NPSH_R$ .....	284
6.3.3 Estimation of the $NPSH_3$ as function of the flow rate.....	288

---

6.4 Influence of the fluid properties .....	291
6.4.1 Thermodynamic effects.....	292
6.4.2 Non-condensable gases .....	294
6.4.3 Nuclei content and tensile stresses in the liquid.....	295
6.5 Cavitation-induced noise and vibrations.....	298
6.5.1 Excitation mechanisms.....	298
6.5.2 Cavitation noise measurements for quantifying the hydro-dynamic cavitation intensity .....	299
6.5.3 Frequency characteristics of cavitation noise.....	302
6.6 Cavitation erosion .....	303
6.6.1 Testing methods .....	304
6.6.2 Cavitation resistance .....	306
6.6.3 Prediction of cavitation damage based on cavity length .....	309
6.6.4 Prediction of cavitation damage based on cavitation noise .....	312
6.6.5 Solid-borne noise measurements for cavitation diagnosis .....	314
6.6.6 Paint erosion tests to determine the location of bubble implosion ...	314
6.6.7 Onset of erosion and behavior of material subject to different hydrodynamic cavitation intensities .....	316
6.6.8 Summarizing assessment.....	319
6.7 Selection of the inlet pressure in a plant .....	323
6.8 Cavitation damage: analysis and remedies .....	326
6.8.1 Record damage and operation parameters.....	326
6.8.2 Forms of cavitation and typical cavitation damage patterns .....	327
6.8.3 Reduction or elimination of cavitation damage.....	332
6.9 Insufficient suction capacity: Analysis and remedies .....	333
<b>7 Design of the hydraulic components.....</b>	<b>335</b>
7.1 Methods and boundary conditions .....	335
7.1.1 Methods for the development of hydraulic components .....	335
7.1.2 The hydraulic specification .....	336
7.1.3 Calculation models .....	337
7.2 Radial impellers .....	339
7.2.1 Determination of main dimensions .....	339
7.2.2 Impeller design.....	348
7.2.3 Criteria for shaping the blades .....	353
7.2.4 Criteria for suction impeller design.....	356
7.2.5 Exploiting three-dimensional effects in design .....	358
7.3 Radial impellers for specific speeds below $n_q \approx 18$ .....	359
7.3.1 Two-dimensional blades .....	359
7.3.2 Pumping disks with channels of circular section .....	361
7.3.3 Impellers with straight radial blades .....	363
7.3.4 Double-acting impeller with straight radial blades .....	364
7.4 Radial impellers for non-clogging pumps .....	366
7.5 Semi-axial impellers .....	368
7.6 Axial impellers and diffusers .....	373

7.6.1 Features .....	373
7.6.2 Calculation and selection of main dimensions .....	374
7.6.3 Basic properties of airfoils .....	379
7.6.4 Blade design.....	383
7.6.5 Profile selection.....	388
7.6.6 Design of axial diffusers .....	390
7.7 Inducers .....	392
7.7.1 Calculation of inducer parameters.....	393
7.7.2 Design and shaping of an inducer .....	398
7.7.3 Matching the inducer to the impeller .....	399
7.7.4 Recommendations for inducer application.....	400
7.8 Volute casings .....	402
7.8.1 Calculation and selection of main dimensions .....	402
7.8.2 Design and shaping of volute casings .....	406
7.8.3 Influence of the volute shape on hydraulic performance .....	410
7.9 Radial diffusers with or without return channels.....	412
7.9.1 Calculation and selection of main dimensions .....	412
7.9.2 Design and shaping of radial diffusers.....	418
7.10 Semi-axial diffusers.....	421
7.11 Volutes combined with a diffuser or stay vanes.....	422
7.12 Annular casings and vaneless diffusers .....	423
7.13 Inlet casings for between-bearing pumps .....	424
<b>8 Numerical flow calculations .....</b>	<b>429</b>
8.1 Overview .....	429
8.2 Quasi-3D-procedures and 3D-Euler-calculations.....	431
8.2.1 Quasi-3D- procedures .....	431
8.2.2 Three-dimensional Euler-procedures .....	432
8.3 Basics of Navier-Stokes calculations.....	433
8.3.1 The Navier-Stokes equations .....	433
8.3.2 Turbulence models .....	434
8.3.3 Treatment of near-wall flows .....	439
8.3.4 Grid generation .....	441
8.3.5 Numerical procedures and control parameters .....	444
8.3.6 Boundary conditions .....	446
8.3.7 Initial conditions .....	448
8.3.8 Possibilities of 3D-Navier-Stokes-calculations.....	449
8.4 Averaging and post-processing .....	452
8.5 Impeller calculations.....	459
8.5.1 Global performance at best efficiency flow rate .....	459
8.5.2 Velocity profiles.....	462
8.5.3 Influence parameters .....	463
8.5.4 Sample calculation .....	463
8.6 Calculation of collectors and stages .....	466
8.6.1 Separate calculation of the collector .....	466

---

8.6.2 Steady calculations of stages or complete pumps .....	467
8.6.3 Unsteady calculations.....	469
8.7 Two-phase and cavitating flows .....	470
8.8 Calculation strategy, uncertainties, quality issues .....	473
8.8.1 Uncertainties, sources and reduction of errors .....	473
8.8.2 CFD quality assurance .....	475
8.8.3 Comparison between calculation and experiment .....	486
8.9 Criteria for assessment of numerical calculations.....	488
8.9.1 General remarks .....	488
8.9.2 Consistence and plausibility of the calculation .....	488
8.9.3 Will the specified performance be reached? .....	489
8.9.4 Maximization of the hydraulic efficiency .....	489
8.9.5 Stability of the head-capacity curve .....	492
8.9.6 Unsteady forces .....	492
8.10 Fundamental considerations on CFD-calculations .....	493
<b>9 Hydraulic forces .....</b>	<b>495</b>
9.1 Flow phenomena in the impeller sidewall gaps .....	495
9.2 Axial thrust .....	508
9.2.1 General procedure for calculating axial thrust .....	508
9.2.2 Single-stage pumps with single-entry overhung impeller .....	511
9.2.3 Multistage pumps .....	515
9.2.4 Double-entry impellers.....	519
9.2.5 Semi-axial impellers.....	520
9.2.6 Axial pumps .....	520
9.2.7 Expeller vanes .....	520
9.2.8 Semi-open and open impellers .....	522
9.2.9 Unsteady axial thrust.....	523
9.3 Radial thrust.....	524
9.3.1 Definition and scope .....	524
9.3.2 Measurement of radial forces .....	525
9.3.3 Pumps with single volutes.....	526
9.3.4 Pumps with double volutes .....	531
9.3.5 Pumps with annular casings .....	532
9.3.6 Diffuser pumps.....	533
9.3.7 Radial thrust created by non-uniform approach flows .....	533
9.3.8 Axial pumps .....	535
9.3.9 Radial thrust balancing.....	535
9.3.10 Radial thrust prediction .....	536
<b>10 Noise and Vibrations.....</b>	<b>539</b>
10.1 Unsteady flow at the impeller outlet.....	539
10.2 Pressure pulsations .....	542
10.2.1 Generation of pressure pulsations .....	542
10.2.2 Noise generation in a fluid .....	543

10.2.3 Influence parameters of the pump .....	544
10.2.4 Influence of the system .....	545
10.2.5 Scaling laws .....	546
10.2.6 Measurement and evaluation of pressure pulsations .....	547
10.2.7 Pressure pulsations of pumps in operation .....	549
10.2.8 Damaging effects of pressure pulsations .....	552
10.2.9 Design guidelines .....	552
10.3 Component loading by transient flow conditions .....	553
10.4 Radiation of noise .....	555
10.4.1 Solid-borne noise .....	555
10.4.2 Air-borne noise .....	556
10.5 Overview of mechanical vibrations of centrifugal pumps .....	559
10.6 Rotor dynamics .....	561
10.6.1 Overview .....	561
10.6.2 Forces in annular seals .....	562
10.6.3 Hydraulic impeller interaction .....	569
10.6.4 Bearing reaction forces .....	570
10.6.5 Eigen values and critical speeds .....	571
10.6.6 Rotor instabilities .....	574
10.7 Hydraulic excitation of vibrations .....	577
10.7.1 Interactions between impeller and diffuser blades .....	577
10.7.2 Rotating stall .....	581
10.7.3 Other hydraulic excitation mechanisms .....	582
10.8 Guidelines for the design of pumps with low sensitivity to vibrations ..	586
10.9 Allowable vibrations .....	589
10.10 General vibration diagnostics .....	592
10.10.1 Overview .....	592
10.10.2 Vibration measurements .....	593
10.10.3 Vibration diagnostics .....	595
10.11 Bearing housing vibrations: mechanism, diagnostics, remedies ..	601
10.11.1 Hydraulic excitation mechanisms .....	602
10.11.2 Mechanical reaction to hydraulic excitation .....	606
10.11.3 Hydraulic versus mechanical remedies .....	608
10.11.4 Bearing housing vibration diagnostics .....	610
10.12 Hydraulic and acoustic excitation of pipe vibrations .....	621
10.12.1 Excitation of pipe vibrations by pumps .....	622
10.12.2 Excitation of pipe vibrations by components .....	624
10.12.3 Acoustic resonances in pipelines .....	624
10.12.4 Hydraulic excitation by vortex streets .....	629
10.12.5 Coupling of flow phenomena with acoustics .....	631
10.12.6 Pipe vibration mechanisms .....	635
<b>11 Operation of centrifugal pumps .....</b>	<b>639</b>
11.1 System characteristics, operation in parallel or in series .....	639
11.2 Pump control .....	644

---

11.3 Static and dynamic stability .....	651
11.4 Start-up and shut-down .....	653
11.5 Power failure, water hammer .....	657
11.6 Allowable operation range .....	658
11.7 The approach flow to the pump .....	661
11.7.1 Suction piping layout .....	662
11.7.2 Transient suction pressure decay .....	664
11.7.3 Pump intakes and suction from tanks with free liquid level .....	670
11.7.4 Can pumps .....	685
11.8 Discharge piping .....	685
<b>12 Turbine operation, general characteristics .....</b>	<b>689</b>
12.1 Reverse running centrifugal pumps used as turbines .....	689
12.1.1 Theoretical and actual characteristics .....	689
12.1.2 Runaway and resistance characteristics .....	695
12.1.3 Estimation of turbine characteristics from empirical correlations ..	696
12.1.4 Behavior of turbines in plants .....	701
12.2 General characteristics .....	704
<b>13 Influence of the medium on performance .....</b>	<b>711</b>
13.1 Pumping highly viscous fluids .....	711
13.1.1 Effect of viscosity on losses and performance characteristics .....	711
13.1.2 Estimation of viscous performance from the characteristics measured with water .....	718
13.1.3 Influence of viscosity on the suction capacity .....	724
13.1.4 Start-up of pumps in viscous service .....	725
13.1.5 Viscous pumping applications - recommendations and comments ..	725
13.2 Pumping of gas-liquid mixtures .....	727
13.2.1 Two-phase flow patterns in straight pipe flow .....	727
13.2.2 Two-phase flow in pumps. Physical mechanisms .....	730
13.2.3 Calculation of two-phase pump performance .....	740
13.2.4 Radial pumps operating with two-phase flow .....	746
13.2.5 Helico-axial multiphase pumps .....	752
13.2.6 System curves .....	756
13.2.7 Slugs and gas pockets .....	757
13.2.8 Free gas, dissolved gas and NPSH .....	759
13.3 Expansion of two-phase mixtures in turbines .....	760
13.3.1 Calculation of the work transfer .....	760
13.3.2 Prediction of turbine characteristics for two-phase flow .....	762
13.4 Hydraulic transport of solids .....	765
13.5 Non-Newtonian liquids .....	773
<b>14 Selection of materials exposed to high flow velocities .....</b>	<b>777</b>
14.1 Impeller or diffuser fatigue fractures .....	778
14.2 Corrosion .....	790

14.2.1 Corrosion fundamentals .....	790
14.2.2 Corrosion mechanisms .....	791
14.2.3 Corrosion in fresh water, cooling water, sewage .....	795
14.2.4 Corrosion in sea water and produced water .....	798
14.3 Erosion corrosion in demineralized water .....	803
14.4 Material selection and allowable flow velocities.....	812
14.4.1 Definition of frequently encountered fluids .....	812
14.4.2 Metallic pump materials.....	814
14.4.3 Impellers, diffusers and casings .....	820
14.4.4 Wear ring materials .....	831
14.4.5 Shaft materials.....	834
14.4.6 Materials for feedwater and condensate pumps .....	835
14.4.7 Materials for FGD-pumps .....	836
14.4.8 Composite materials .....	837
14.5 Hydro-abrasive wear .....	839
14.5.1 Influence parameters .....	839
14.5.2 Quantitative estimation of hydro-abrasive wear .....	842
14.5.3 Material behavior and influence of solids properties .....	848
14.5.4 Material selection .....	852
14.5.5 Abrasive wear in slurry pumps .....	853
<b>15 Pump selection and quality considerations .....</b>	<b>857</b>
15.1 The pump specification .....	858
15.2 Determination of pump type and size .....	860
15.3 Technical quality criteria .....	866
15.3.1 Hydraulic criteria .....	866
15.3.2 Manufacturing quality .....	870
15.4 High-energy pumps .....	875
<b>Appendices .....</b>	<b>881</b>
A1 Units and unit conversion .....	881
A2 Properties of saturated water .....	883
A3 Solution of gases in water.....	886
A4 Physical constants.....	889
A4.1 Atmospheric pressure .....	889
A4.2 Acceleration due to gravity .....	889
A5 Sound velocity in liquids .....	890
<b>Literature .....</b>	<b>891</b>
<b>Index.....</b>	<b>917</b>
<b>List of tables.....</b>	<b>XIX</b>
<b>Symbols and abbreviations.....</b>	<b>XXIII</b>