

CONTENTS

	PAGE
<i>Prefaces</i>	v
<i>List of Tables</i>	xvii
<i>The Meaning of Symbols Used throughout the Work</i>	xxi

CHAPTER I

INTRODUCTION	1
Principle of action of steam turbine—The simple impulse steam turbine—The pressure-compounded impulse turbine—Simple velocity-compounded impulse turbine—Pressure-velocity-compounded turbine—Pure reaction turbine—Axial-flow impulse-reaction turbine—The radial-flow double-motion reaction turbine—Combination turbines	

CHAPTER II

PROPERTIES OF STEAM	15
Introduction—Unit of heat—Unit of work—Heat and work—Relationship between temperature and vapour pressure—Sensible heat of water—Latent heat—Heat of generation—Dryness fraction—Superheated steam—The enthalpy function—The enthalpy of water—The enthalpy of steam—Specific volume of steam—Examples	

CHAPTER III

ENTROPY DIAGRAMS	38
The entropy function—The temperature-entropy diagram for steam—The enthalpy-entropy diagram— T - ϕ and ϕ - I diagrams for compressed water—Thermodynamic potential—Examples	

CHAPTER IV

THEORETICAL STEAM TURBINE CYCLE	54
Definition of cycle—Actual steam turbine cycle—Rankine cycle for steam initially saturated—Rankine cycle for steam initially superheated—Superheated steam cycle with superheated exhaust—Thermal efficiency ratio—Examples	

CHAPTER V

THE FLOW OF STEAM THROUGH NOZZLES	73
Introduction—Equation of continuity—Steady flow equation for turbine, nozzle, blades, etc.—The momentum equation for the flow through a turbine nozzle—Entropy changes with friction—Adia-	

batic equation for steam—Calculation of nozzle area in general case of adiabatic and frictionless flow—Proof of the existence of a critical pressure in nozzle flow—Physical explanation of critical pressure—Maximum discharge of saturated steam—Maximum discharge of steam initially superheated—General relationship between area, velocity and pressure in nozzle flow—Adiabatic and frictionless expansion of steam from a given initial velocity—Friction in turbine nozzles—Viscosity of steam—The meaning of nozzle efficiency—Effect of friction on the critical pressure ratio—Critical pressure ratio in a frictionally resisted expansion from a given initial velocity—To calculate the mass flow through a convergent nozzle, given the inlet and outlet areas and pressures—Calculation of friction loss in a turbine nozzle—Secondary flows in turbine nozzles—Experimental measurements of steam discharge through nozzles—Supersaturation in steam turbine nozzles—Equations for supersaturated steam—The Kelvin-Helmholtz equation—Jet deflection in turbine nozzles—Examples

CHAPTER VI

STEAM NOZZLE RESEARCH 144

Introduction—Reaction method of measuring velocity—Impulse method of measuring velocity—Search-tube method of determining pressure distribution in a nozzle—Stodola's search-tube experiments—Experimental results obtained with reaction apparatus—Institution of Mechanical Engineers' steam nozzles research—Apparatus—Results of tests—Velocity coefficients at low steam velocities—The relationship between the velocity coefficient and the efficiency of a nozzle—The use of air for steam nozzle testing—Experiments on reaction turbine nozzles—Further steam nozzle tests

CHAPTER VII

THE FLOW OF STEAM THROUGH IMPULSE TURBINE BLADES 172

Velocity diagrams for impulse turbine—Forces on blades—Influence of ratio of blade speed to steam speed on blade efficiency in single-stage turbine—Gross stage efficiency—Efficiency of multi-stage impulse turbine with single-row wheels—Impulse blade sections—Choice of blade angles—Velocity-compounded impulse turbine—Velocity diagram for typical velocity-compounded wheel—Most economical ratio of blade speed to steam speed for a two-row wheel—Blade heights in velocity-compounded wheels—Advantages and disadvantages of velocity-compounding—Examples

CHAPTER VIII

THE FLOW OF STEAM THROUGH IMPULSE-REACTION TURBINE BLADES 208

The meaning of impulse-reaction—Degree of reaction—Impulse-reaction turbine with similar blade sections and half-degree reaction (Parsons turbine)—Height of reaction blading—Stage efficiency of impulse-reaction turbine with half-degree reaction—Operation of impulse blading with varying heat drop or variable speed—Examples

CONTENTS

xi

CHAPTER IX

VORTEX FLOW IN STEAM TURBINES 228

Introduction—Equation of equilibrium—Equation of continuity—Energy equation—Constant specific mass flow—Simplified analysis for uniform nozzle outlet angle—Vortex flow with constant axial velocity at outlet from the nozzles—General notes on vortex flow

CHAPTER X

EXPERIMENTS ON TURBINE BLADES 248

Early experiments—Faltin's experiments—Secondary flows in turbine blades—Air tests on model blades—Efficiency of short blades—Newer forms of turbine blades—Tests of impulse-reaction blades

CHAPTER XI

INTERNAL LOSSES IN STEAM TURBINES 268

Introductory—Disc friction—Partial admission losses—Gland leakage losses—Flow of steam through labyrinth packing—Hydraulic glands—Advantages and disadvantages of hydraulic glands—Residual velocity loss—Examples

CHAPTER XII

STATE POINT LOCUS AND REHEAT FACTOR 290

Stage efficiency of impulse turbines—State point locus on ϕ -I diagram for a single stage of an impulse turbine—State point locus for multi-stage turbine—Condition curves—Correction for terminal velocity—Reheat factor—Reheat factor for an expansion with a uniform adiabatic index and a constant-stage efficiency—Reheat factors for steam expanding wholly in the superheat region—Reheat factors for steam which is initially dry and saturated and expands in thermal equilibrium—Correction for finite number of stages—Reheat factors for steam expanding partly in the superheated condition and partly in the saturated condition—Internal efficiency—Examples

CHAPTER XIII

REGENERATIVE FEED-HEATING 307

Introductory—Feed-heating systems—Gains due to regenerative feed-heating—Ideal feed-heating cycle—General notes on feed-heating—Examples

CHAPTER XIV

REHEATING AND WATER-EXTRACTION CYCLES 324

Flow of wet steam in nozzles and blades—Correction to condition curve for wetness—Erosion of blades—Reheating—Notes on reheating—Regenerative water-extraction cycle—Examples

	PAGE
CHAPTER XV	
TURBINE PERFORMANCE AT VARYING LOADS	353
Methods of governing—Throttle governing—Pressure distribution at varying loads with throttle governing—Throttle governing in reaction turbines—Nozzle control governing—Nozzle-box pressures with nozzle control governing—Condition curve with nozzle control governing—Comparison of throttle and nozzle control governing—By-pass governing—Theory of by-pass governing—By-pass governing of reaction turbines—Examples	
CHAPTER XVI	
MIXED-PRESSURE TURBINES	377
Low-pressure turbines—The Larderello natural steam power plant—Mixed-pressure turbine—Conditions of operation of mixed-pressure turbine—Theory of heat accumulator—Examples	
CHAPTER XVII	
BACK-PRESSURE AND PASS-OUT TURBINES	389
Introductory—Back-pressure turbines—Pass-out turbine—Operation of pass-out turbine with single extraction—Steam consumption curves of pass-out turbine—Examples	
CHAPTER XVIII	
CONSTRUCTION OF NOZZLES AND DIAPHRAGMS	404
Introductory—First-stage convergent nozzles—Materials and preparation of nozzle guide blades—Built-up nozzle—Diaphragm nozzles—The de Laval nozzle—Machined type of nozzle—"Cast-in" type of convergent-divergent nozzles—Built-up nozzle—Loss due to steam entering blades obliquely and special form of nozzle to minimize such loss—Strength and stiffness of turbine diaphragms	
CHAPTER XIX	
CONSTRUCTION OF TURBINE BLADES AND BLADE ATTACHMENTS	424
Centrifugal stress in turbine blades of uniform cross-section—Bending stresses in symmetrical impulse blades of uniform cross-section—Graphics of blade sections—Bending stresses in reaction blades—Special form of long blades—General notes on the attachment of turbine blades—De Laval blade attachment—Inverted-T attachment—Stresses in wheel rims—Serrated blade root—Fitting of blades in wheel—Blade attachment for high-pressure Curtis wheel—Straddle attachment—Modified straddle attachment—Side entry blades—Attachment of shrouding strip—Attachment of Parsons reaction turbine blades—Parsons end-tightened blading—Parsons integral blades—Blade materials—Examples	
CHAPTER XX	
CONSTRUCTION OF TURBINE ROTORS	458
De Laval rotors—Construction of disc rotors—Mounting of wheels on shafts—Rotors machined from solid forgings—Rotors for	

CONTENTS

xiii

reaction turbines—Brown-Boveri drum rotor—Brown-Boveri welded rotor—Balancing of the steam thrust on the moving blades of reaction turbines—Proportions of dummy balance pistons—Couplings

PAGE

CHAPTER XXI

STRESSES IN TURBINE ROTORS 480

Introductory—Stress in thin rotating ring—Stresses in turbine rotors of the drum type—Stresses in rotating discs of variable thickness: derivation of general equations—Disc of constant thickness—Continuous disc of constant thickness—Disc of constant thickness with central hole—Stresses in turbine wheel of constant thickness—Discs of hyperbolic section—Stress analysis in rotors by method of superposition—Force-fit allowance for wheels pressed or shrunk on shaft—The disc of constant stress—Effect of holes in discs—Pre-stressing by overspeeding—Materials and working stresses—Examples

CHAPTER XXII

THE CRITICAL SPEED OF TURBINE ROTORS 516

Definition—Balancing—Small-diameter shaft supporting a single wheel—Rayleigh's approximate solution for the fundamental frequency of a single-span beam or shaft—Uniform shaft with uniformly distributed load, ends freely supported—Other critical speeds—Uniform shaft with uniformly distributed loads, ends fixed—Comparison of "free" and "fixed" ends of shafts—Dunkerley's semi-empirical formula for the first critical speed of a uniform shaft carrying a number of concentrated loads—Critical speed of a shaft of variable cross-section and loaded by a number of concentrated loads—Relationship between critical speed and maximum static deflection—Approximate determination of spindle diameter—Examples

CHAPTER XXIII

CONSTRUCTION OF CYLINDERS 540

Form of cylinder—Horizontal joint flange—Flange bolts—Parsons clamped joint construction—Nozzle-box construction—Double-cylinder construction—Construction of exhaust end—Cylinder supports—Materials

CHAPTER XXIV

GLANDS AND PACKING DEVICES 558

Diaphragm glands—External glands of the labyrinth type—Forms of labyrinth packing—Carbon-ring glands—Packing of balance pistons in Parsons turbines

CHAPTER XXV

BEARINGS AND LUBRICATION 573

Introduction—Beauchamp Tower's experiments—Conditions essential for film lubrication—The journal bearing—Construction of journal bearings—Materials—Design of journal bearings—The

journal centre locus—Conditions during stopping and starting—Turning gear—Thrust bearings—Plain and bevelled collar bearings—Tilting pad thrust bearings—Construction of Michell thrust bearings—Plain collar thrust bearing with fixed inclined thrust surfaces—Forced lubrication systems

CHAPTER XXVI

GOVERNORS AND GOVERNOR GEARS 610

Introduction—The governor—Simple governor without relay—Simple throttle governor with oil relay—Speeder gear—Alternative form of oil relay—The throttle valve—Flow of superheated steam through throttle valves—Design of simple throttle valve—Modified linkages to give a closer approach to straight-line regulation—Design of shaped throttle valve—Nozzle control governor gear—Oil pressure governing without linkage—Compound oil relay—Governor gear for mixed-pressure turbine—Governor gear for pass-out turbine—Fluid-pressure governors—Early Parsons air governor—Westinghouse fluid-pressure governor—Westinghouse fluid-pressure governor with governor transformer—Speeder gear—Governor anticipatory gear—Vacuum unloading and trip gear

CHAPTER XXVII

SPEED AND OUTPUT OF STEAM TURBINES 663

Relationship between cumulative heat drop, mean diameter, speed of rotation, and number of stages in impulse turbines—Relationship between cumulative heat drop, mean diameter, speed of rotation, and number of stages in reaction turbines—Comparison of pressure-compounded and velocity-compounded turbines—Relationship between output, speed, and blade velocity in impulse turbines—Relationship between output, speed, and blade velocity in reaction turbines—Turbine output and stress in last row of blades—Carry-over loss—Conditions in turbines with vortex flow—Methods of increasing the limiting output of steam turbines—Multi-exhaust turbines—The Baumann multi-exhaust turbine—Examples

CHAPTER XXVIII

THE LJUNGSTRÖM TURBINE 691

Theory of the Ljungström turbine—Optimum ratio of blade speed to steam speed—Calculation of blade lengths—Relationship between cumulative heat drop, speed of rotation, number of blade rings, and diameter of blade rings in the Ljungström turbine—General description—Blade construction—Disc construction—Balancing arrangements—Shaft glands—Multiple radial-flow turbine—General notes

CHAPTER XXIX

EXAMPLES OF CONSTRUCTION 724

Turbines for electricity generating stations—60 MW. English Electric turbine—200 MW. English Electric turbine—30 MW. General Electric Co. steam turbine—120 MW. General Electric steam turbine—General Electric 200 MW. turbine—30 MW. Metrovick steam turbine—100 MW. Metrovick steam turbine—Parsons

CONTENTS

XV

60 MW. turbine—125 MW. Parsons steam turbine—60 MW. Richardsons Westgarth—Brown-Boveri steam turbine—Brush back-pressure turbine—Escher Wyss back-pressure turbines—Marine turbines—Pametrada marine turbines—Metropolitan-Vickers marine turbines—English Electric marine turbines for H.M. "Daring" class destroyers—English Electric marine turbines for H.M. frigates of the "Blackwood" class—Steam turbines for nuclear power stations—Control gear for Calder Hall turbines—Turbines for the nuclear power station in Ayrshire

PAGE

CHAPTER XXX

TEST RESULTS	802
------------------------	-----

Objects of testing—Test apparatus—Correction factors—Tests on single-wheel de Laval turbines—Tests on 15,000 kW impulse turbine—Tests on 35,000 kW impulse turbine—Tests on 11,000 kW impulse turbine—Tests on 10,000 kW impulse turbine operating with steam at 1,000° F.—Tests on 1,000 kW back-pressure combination turbine—Tests on 36,000 kW steam turbine operating with steam at 1,700 lb. per square inch absolute and with live steam reheating—Tests on a 40,000 kW Parsons turbine with flue-gas reheating—Test results for Ljungström turbines—Tests on 100,000 kW. non-reheat turbo-generator—Tests on British 30 MW. and 60 MW. turbo-generators

APPENDIX

MATERIALS FOR STEAM TURBINES	837
Creep of metals—Stress to rupture—Resistance to scaling—Turbine cylinders—Turbine rotors	
<i>Answers to Examples</i>	843
<i>Name Index</i>	849
<i>Subject Index</i>	851

INSETS

60,000 KW STEAM TURBO-ALTERNATORS	<i>Frontispiece</i>
	<i>Facing page</i>
FIG. 430. 2,500 KW WESTINGHOUSE TURBINE, WITH OIL GOVERNOR	650
FIG. 472. ENGLISH ELECTRIC 60 MW TURBINE	726
FIG. 529. PARSONS 21,000 KW TURBINE FOR CALDER HALL POWER STATION	795