

Table of Contents

Abstract	V
Symbols and Abbreviations	XI
1 Introduction	1
1.1 Dry-Running Screw Spindle Vacuum Pumps	3
1.1.1 Classification and Working Principle	3
1.1.2 Simulation of Screw Vacuum Pumps	6
1.2 Investigation of Gas Flows	8
1.2.1 Poiseuille Flow	8
1.2.2 Couette Flow	9
1.2.3 Thermal Creep Flow	9
1.2.4 Mixed Flows	10
1.3 Gas-Surface Interactions	10
2 Aim of the Work and Approach	13
3 Basics of Rarefied Gas Dynamics	15
3.1 Molecular Model	15
3.2 Conservation Laws	16
3.3 Principle of Relativity	17
3.4 Binary Collisions	18
3.5 Kinetic Gas Theory	20
3.5.1 Macroscopic Gas Properties	22
3.5.2 Distribution Function	24
3.5.3 Boltzmann Equation	26
3.5.4 Maxwell-Boltzmann Distribution	27
3.5.5 Gas-Surface Interactions	28
3.6 Macroscopic Conservation Equations	30
3.6.1 Continuum Model	31
3.6.2 Velocity Slip and Temperature Jump	32
3.6.3 Dimensional Analysis and Simplifications	33
4 Numerical Methods	37
4.1 Computational Fluid Dynamics (CFD)	37

4.1.1	Discretisation	37
4.1.2	Boundary Conditions	40
4.2	Direct Simulation Monte Carlo (DSMC) Method	41
4.2.1	Algorithm	42
4.2.2	Particle Movement	43
4.2.3	Boundary Conditions	43
4.2.4	Binary Collisions	45
4.2.5	Macroscopic Properties	45
4.2.6	Error Estimation	46
5	Working Chambers in Vacuum Spindle Pumps	47
5.1	Kinematics and Geometric Abstraction	47
5.2	Dimensional Analysis	49
5.3	Thermodynamic Model for Closed Chambers	50
5.4	Strouhal Number for Open Chambers	52
6	Reduced Flow Rates	53
6.1	Poiseuille Flow	53
6.1.1	Slip Regime	54
6.1.2	Transitional Regime	59
6.1.3	DSMC Model	60
6.1.4	Validation	61
6.1.5	Contour Plots	64
6.2	Couette Flow	65
6.2.1	Properties of the Couette Flow	66
6.2.2	Hydrodynamic Regime	67
6.2.3	Slip Regime	68
6.2.4	Free Molecular Regime	69
6.2.5	Transitional Regime	72
6.2.6	Validation	74
6.2.7	Contour Plots	76
6.3	Applications and Application Limits	79
6.3.1	Poiseuille Flow	79
6.3.2	Couette Flow	80
6.3.3	Couette-Poiseuille Flow	81
7	Inhomogeneous Chamber States	83
7.1	CFD Model	83
7.2	Validation of the 1D Model	84
7.3	Approximative Functions Depending on the Dimensionless Pressure Gradient	91
8	Experimental Investigations	95
8.1	Test Rig	95
8.2	Sensors	98
8.3	Method of Measurement	99
8.4	Leakage	99

8.5	Uncertainty	101
8.5.1	Pressure	102
8.5.2	Temperature	102
8.5.3	Rotational Speed	104
8.5.4	Geometry	104
8.5.5	Uncertainties of Dimensionless Numbers	104
8.6	1D Modelling of the Test Rig	104
8.7	Comparison Between Measurements and 1D Model Simulation	106
8.8	Conclusion	114
9	Transient Chamber Filling	115
9.1	Domain and Boundary Conditions	115
9.2	Error Estimation	117
9.3	Strouhal Number	118
9.4	Comparison Between Transient and Quasi-Static Chamber Filling	124
10	Chamber Model Simulation	127
10.1	The Simulation Tool <i>KaSim</i>	127
10.2	Inhomogeneous Chamber States	131
10.3	Gap Flow Models	133
10.3.1	Theoretical Mass Flow Rates	133
10.3.2	Friction Models	134
10.4	Geometry Model	137
10.4.1	Mathematical Rotor Description	139
10.4.2	Volume Curves and Opening Areas	141
10.4.3	Housing Gap	142
10.4.4	Radial Gap	142
10.4.5	Blow Hole	143
10.4.6	Inter-Lobe Gap	143
10.5	Simulation of a Test Machine	144
11	Conclusion and Outlook	149
Bibliography		152
Appendix		163
A Proof of Couette Flow Properties		165
A.1	Shape Factor	165
A.2	High Wall Velocities	165
A.3	Superposition Principle	166
B DSMC Data		167
C Experimental Setup		171
D Measurement Data		173