

### CENTRIFUGAL PUMP DESIGN AND PERFORMANCE OPTIMIZATION USING LOSS CORRELATIONS

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### Outline

#### Introduction

#### Pump Theory

- Design of impeller and volute
- Loss models
- Code implementation and CFD analysis
- Results & Discussion
  - Prediction results
  - CFD Results
  - Comparison
- □ Future Work

### Introduction

- Flow inside the pump
  - Highly complicated
  - Can be successfully simulated using CFD
- Predicting the pump performance characteristics without
  - performing the time consuming and challenging CFD calculations



#### The aim of this thesis

To develop a pump performance prediction code using theoretical and empirical energy loss equations from the literature

### Introduction Literature

- There are well known books on pump design topic by Pfleiderer, Gülich and Tuzson
- Loss correlations of Hamkins and Dick are performed for the prediction off-design conditions
- Wiesner developed a formula for the prediction of slip factors
- Blade loading losses are calculated via Pearsall's formula adapted to centrifugal pumps by Myles
- Various CFD simulation models of centrifugal pumps have been presented in literature

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## Pump Theory

Three characteristic dimensions should be known in the design calculation of a centrifugal pump

- *H<sub>m</sub>*: Delivery head (m)
- Q: Flow rate (m<sup>3</sup>/s)
- n: Rotational speed (rpm)



### Pump Theory Design of impeller

Main dimensions of impeller

- $D_1$  = Inlet diameter
- $b_1$  = Inlet blade width
- $b_2$  = Outlet blade width
- D<sub>s</sub> = Pump shaft diameter
- $D_h$  = Impeller hub diameter



### Pump Theory Design of impeller



Outlet conditions



The velocity triangle is described by three vectors:

Circumferential velocity, u

multiplication of angular velocity  $\boldsymbol{\omega}\text{,}$  and impeller radius r

- $D_2 \ge$  Relative velocity, **w** 
  - Absolute velocity, c

which is obtained through the vectorial addition of u and w

### Pump Theory Design of volute

The gradually increasing volute flow cross sections are calculated from the flow rate and from an average velocity at the volute cross section center.

The usual flow model assumes that the impeller outlet tangential velocity decreases in proportion to the radius to maintain constant angular momentum.



### Pump Theory Loss models

- Theoretical head
- Slip factor
- Inlet loss
- Impeller losses
   Mismatching loss
   Friction loss
   Blade loading loss
- Volute losses
   Mismatching loss
   Friction loss
   Diffusor loss

Disc friction loss



### Pump Theory Loss models

Theoretical head (H<sub>m</sub>) is calculated from Euler's pump equation, which gives the conservation of angular momentum across the impeller.

The slip phenomenon has a strong influence on the working condition of centrifugal pumps. several methods have been proposed by a large number of authors, Stodola, Busemann, Stanitz, Wiesner, Backström etc.

□ Wiesner obtained an empirical formula that predicts the slip factor,  $\sigma$ . The formula includes the relation of outlet blade angle  $\beta_2$ , and number of blades, *Z*.

### Pump Theory Loss models

□ Tangential component of the absolute velocity  $cu_2$  can be found by extracting tangential component of the relative velocity  $wu_2$  from the peripheral velocity  $u_2$ , by taking into account of slip factor as  $\sigma u_2$ 



### Pump Theory Code implementation

The pump design and performance optimization software has been implemented on Java 1.8 using Java FX.

Eclipse which is an integrated development environment (IDE) is used in computer programming. The user interface has been created and edited using the Scene Builder software which is integrated with JavaFx.



### Pump Theory Code implementation



### Pump Theory Code implementation

- Delivery head at design point and offdesign conditions are obtained.
- The design can be modified if the final results are below the desired values by returning to the previous window.
- Iterations end by obtaining the performance curve

Losses						) ×
Theoretical Hth		Impeller Loss	es		Volute Losses	5
Head	Inlet	Loss H0	m	Mismato	hing Hv1	m
Disk Friction Hdf	m Misr	natching Hi1	m	Loss		
	Loss	ller		Friction	Hv2 Loss	m
RESULTING HEAD	Fricti	on Loss Hi2	m	Diffusor	Hd	
H	Blade	Hi3	m	Loss	Tiu	m
		ing Loss		) —		
Losses	Q1	Q2	Q3	Q4	Q5	Q6
Theoretical Head						
Disk Friction Loss						
Inlet Loss						
Impeller Mismatching						
Impeller Friction Loss						
Blade Loading Loss						
Volute Mismatching						
Volute Friction Loss						
Diffusor Loss						
TOTAL HEAD						

#### Solid modeling

Creating domains





Meshing

• Impeller domain have a critical role for calculations. Therefore impeller has more elements compare to inlet and outlet.

• Interiors between impeller - inlet domain and impelleroutlet domain have smaller mesh size due to higher accuracy of analysis.



### Meshing

- Boundary layer mesh (inflation) was applied and layer compression method is selected to preserve the number of layers
- The quality of the resulting grid was checked with the skewness parameter





### Solver settings

- The fluid is incompressible and the rotation of the impeller was performed with MRF (Multiple Reference Frame)
- Steady state analysis were performed.
- k-ω based Shear Stress
   Transport model was used as the turbulence model
- Static meshing is applied for all domains



Boundary Conditions

Inlet

• The mass flow rate (kg/s) is defined normal to the flow direction of the inlet boundary



#### Outlet

• Static pressure of 0 Pa (atmospheric pressure) was defined at the pump outlet



### Pump Theory Experimental Setup

Pump-1 outlet is connected to G2 T-pipe,

Pump-2 is connected to G1½ T-pipe,

Pump-3 is connected to G1¼ T-pipe.



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### Results and Discussion Loss correlation predictions

The main design parameters

□Flow rate, Q

 $\Box$  Delivery head,  $H_m$ 

Rotational speed, n

The calculations can be repeated for each design until the desired pump performance is achieved



### Results and Discussion Loss correlation predictions – Pump-1

	-		( 1	low Rat	te 60	00 1/mi	n		Volut	e		Theoretical Http 26.38	-	Impeller	Losses		Volute Los	sses
wrap ang angle b2/t	e 110 21 [16 DRAW		Deliv	ery Hea Spee id Densi	id 15 id 25 ity 10	5 m 100 RPN 100 kg/r	4 m <sup>3</sup>	b3 D3 t	11.9 144.0 6	mm 0 144	0 mm	Head Hit 20.56 Disk Friction Hdf 0.58 RESULTING HEAD		Inlet Loss H Mismatching Loss H Impeller H Friction Loss H Blade	10 0.05 111 0.00 112 0.70	m Mism Loss M Volut Fricti m Diffu	te Hv2 ion Loss Hv2	5. 3. 0.
Update 0	Calculatio	an		Viscosit	ty 1	cSt		e v d	2.4	2.1 m/s	mm	m		Loading Loss	113 0.05			
No. Contraction		2012	C	1	Calcula	te						Losses	Q	1 Q2	Q3	Q4	Q5	
Specific Speed	138.8			In	npeller	Inlet		Imp	eller (	Dutlet		Theoretical Head	32.41	30.40	28.39	24.37	22.36	20
n sq	38.05			co	3.17	m/s		už	19.01	m/s		Disk Friction Loss	1.17	0.88	0.70	0.50	0.44	0.
D0 nominal	67.99	70	mm	C1	3.33	~ 3.49	m/s	02	125.2	142	ensites	Impeller Mismatching	0.77	0.33	0.03	0.12	0.43	0
Hydraulic Eff.	85.00	5		Cm1	3.15	m/s		u2	21.56	m/s		Impeller Friction Loss	0.17	0.31	0.48	0.95	1.24	1
Volumetric Eff	07 59			01	65.0	-		Cm2	2.45	m/s		Blade Loading Loss	0.00	0.00	0.01	0.11	0.17	0
voidine one en.	37.33	100			03,0			~	0.03			Volute Mismatching	9.54	7.96	6.52	4.07	3.06	2
Mechanical Eff.	97.0	76		010	73.0	mm		cue	0.00	ing 2		Volute Friction Loss	0.83	1.47	2.30	4.51	5.90	7.
Overall Eff.	80.41	%		011	57.0	mm		Hmax	23.70	m		Diffusor Loss	0.15	0.26	0.41	0.80	1.04	1.
Output Power	1.47	kW		u1	9.87	m/s		β2-0	10.2	•		TOTAL HEAD	22.10	20.93	19,26	14.25	10.88	6.
Input Power	1.83	kW		uld	11.08	m/s		82	26	* 16.8		34						
Torque	6.02	Nm		uli	8.66	m/s		z	6	7.1		32 heoretica	Head		-			
Dshaft	13.67	20	mm	β1-0	17.7	]*		• (	5.0	mm		28						
Dhub	28.0	mm		ß1	22.00	):		3.2	0.85			26						
	Canada	-tornal		ß1d	19.9			b2	11.18	9,9	mm	$\Xi \frac{24}{22}$ Actual	Head	•			-	
Calcul	-1-			β1i	24.0	1	angle b	2/b1	14.0	15	1.	20 10		and the second se				
Loss	es			b1	24.5	mm		21	0.61			H 16						
								61	26.24	19.75	mm	14						
								- 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1		Canada		Total Hea	Los					

Symbol	Value	Unit
D <sub>1</sub>	65	mm
D <sub>2</sub>	142	mm
b <sub>1</sub>	19.75	mm
b <sub>2</sub>	9.9	mm
β1	22	٥
β <sub>2</sub>	26	٥
z	6	-
е	5	mm
n	2900	rpm
Q	600	l/min

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400 500

800

600 700

Flow Rate, I/min

900 1000

0 100 200 300

### **Results and Discussion** Loss correlation predictions – Pump-2

-×

Volute Losses

Q5

15.53

0.34

0.14

0.95

0.85

0.62

2.76

4.24

0.66

5.65

50 100 150 200 250 300 350 400 450 500 Flow Rate l/min

Hv2 2.36 m

Hd 0.37 m

Q6

14.85

0.30

0.18

1.57

1.07

0.75

2.30

5.37

0.84

3.09



Symbol	Value	Unit
D <sub>1</sub>	48	mm
D <sub>2</sub>	106	mm
b <sub>1</sub>	24.5	mm
b <sub>2</sub>	15.6	mm
β1	16	٥
β <sub>2</sub>	24	٥
z	5	-
е	3.5	mm
n	2900	rpm
Q	300	l/min

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2 0 0

### Results and Discussion Loss correlation predictions – Pump-3

wrap angle 105 angle b2/b1 11 DRAW Update Calculation Specific Speed 91.10 n sq 24.96 D0 nominal 39.76 35 Hydraulic Eff. 77.69 % Volumetric Eff. 96.75 % Mechanical Eff. 97.0 % Overall Eff. 72.91 % Output Power 0.18 kW	Fluic Fluic	ny Head         1           ry Head         2           Speed         2           I Density         1           Calcu         1           Impelle         2           C0         2.81           C1         2.95           Cm1         2.00           D1         33.0           D1         38.0	120 I/min 9 m 1900 RPM 1000 kg/m <sup>1</sup> 1 cSt 1 cSt 1 ate r Inlet m/s m/s mm mm	b3 D3 D3 D3 Cmm cmm cmm cmm cmm cmm cmm cmm	Volut 13.1 96.0 5 1.6 3.1 1.6 1.6 1.7 1.25 87.3 14.27 1.52 7.96	e mm 96.0 m mm 1.5 m m/s 0utlet m/s 94 mm m/s m/s	m	Theoretical Hth 14.3 Disk Friction Hdf 0.44 Loss Hdf 0.44 H 7.92 n Losses Theoretical Head Disk Friction Loss Inlet Loss Impeller Mismatching Impeller Friction Loss Blade Loading Loss	4 m m b n 14.91 1.31 0.01 0.37 0.01 0.00	Impetie           Iniet Loss           Mismatching           Loss           Impelier           Friction Loss           Biade           Loading Loss           14.72           0.99           0.02           0.25           0.02           0.02           0.02           0.02	H0 0.04 H1 0.09 H12 0.05 H13 0.00 H13 0.00 U3 14.53 0.79 0.03 0.16 0.03 0.16	m Mism m Volut m m Doss Pricti Diffu; Loss 0.05 0.04 0.07	Volute to hatching Hv1 sor Hv2 sor Hd 0.07 0.01 0.09	3.88         m           2.56         m           0.24         m           0.24         m           0.44         0.08           0.00         0.11           0.00         0.11	$ \begin{array}{c} D_1 \\ D_2 \\ b_1 \\ b_2 \\ \beta_1 \end{array} $	35 94 17.5 12.1 26	mm mm mm mm
DRAW Update Calculation Specific Speed 91.10 n sq 24.96 D0 nominal 39.76 35 Hydraulic Eff. 77.69 % Volumetric Eff. 96.75 % Mechanical Eff. 97.0 % Overall Eff. 72.91 % Output Power 0.18 kW	, Fluic	IDensity         1           /iscosity         1           Calcu         Impelle           C0         2.81           C1         2.95           Cm1         2.00           D1         33.0           D1d         38.0	1000 kg/m cSt late r Inlet m/s m/s mm mm	r t e v_c Im u2 m/s D2 u2 Cm2 Cu2	1.6 df 3.1 13.25 87.3 14.27 1.52 7.96	mm 1.5 m m/s Dutlet m/s m/s m/s m/s	m	H 7.92 n Losses Theoretical Head Disk Friction Loss Inlet Loss Impeller Mismatching Impeller Friction Loss Blade Loading Loss	Q 14.91 1.31 0.01 0.37 0.01 0.00	Q2           14.72           0.99           0.02           0.25           0.02           0.02	HI3 0.00 Q3 14.53 0.79 0.03 0.16 0.03 0.03	m Q4 14.15 0.56 0.05 0.04 0.07	Part Hall Control	0.24 m Q6 13.77 0.44 0.08 0.00 0.11 0.00	$\begin{array}{c} D_2 \\ b_1 \\ b_2 \\ \end{array}$	94 17.5 12.1 26	mm mm mm
Update Calculation         Specific Speed       91.10         n sq       24.96         D0 nominal       39.76       35         Hydraulic Eff.       77.69       %         Volumetric Eff.       96.75       %         Mechanical Eff.       97.0       %         Overall Eff.       72.91       %         Output Power       0.18       kW	5 mm	Calcu Impelle C0 2.81 C1 2.95 Cm1 2.00 D1 33.0 D1d 38.0	r Inlet m/s ~ 3.09 m/s mm mm	v_c Im u2 m/s D2 u2 Cm2 Cu2	df 3.1 apeller C 13.25 87.3 14.27 1.52 7.95	m/s Dutlet m/s 94 mm m/s m/s		Losses Theoretical Head Disk Friction Loss Inlet Loss Impeller Mismatching Impeller Friction Loss Blade Loading Loss	Q 14.91 1.31 0.01 0.37 0.01 0.00	1 Q2 14.72 0.99 0.02 0.25 0.02 0.00	Q3 14.53 0.79 0.03 0.16 0.03 0.00	Q4 14.15 0.56 0.05 0.04 0.07	Q5 13.96 0.49 0.07 0.01 0.09	Q6 13.77 0.44 0.08 0.00 0.11	b <sub>1</sub> b <sub>2</sub> β.	17.5 12.1 26	mm mm
Specific Speed         91.10           n sq         24.96           D0 nominal         39.76         35           Hydraulic Eff.         77.69         %           Volumetric Eff.         96.75         %           Mechanical Eff.         97.0         %           Overall Eff.         72.91         %           Output Power         0.18         kW	mm	Impelle           C0         2.81           C1         2.95           Cm1         2.00           D1         33.0           D1d         38.0	r Inlet m/s ~ 3.09 m/s mm mm	Im u2 m/s D2 u2 Cm2 Cu2	13.25 87.3 14.27 1.52 7.96	Dutlet m/s 94 mm m/s m/s		Theoretical Head Disk Friction Loss Inlet Loss Impeller Mismatching Impeller Friction Loss Blade Loading Loss	14.91 1.31 0.01 0.37 0.01 0.00	14.72 0.99 0.02 0.25 0.02 0.02 0.00	14.53 0.79 0.03 0.16 0.03	14.15 0.56 0.05 0.04 0.07	13.96 0.49 0.07 0.01 0.09	13.77 0.44 0.08 0.00 0.11	b <sub>2</sub> β.	12.1 26	mm •
n sq 24.96 D0 nominal 39.76 35 Hydraulic Eff. 77.69 % Volumetric Eff. 96.75 % Mechanical Eff. 97.0 % Overall Eff. 72.91 % Output Power 0.18 kW	mm	C0 2.81 C1 2.95 Cm1 2.00 D1 33.0 D1d 38.0	m/s ~ 3.09 m/s mm	u2 m/s D2 u2 Cm2 Cu2	13.25 87.3 14.27 1.52	m/s 94 mm m/s m/s		Inlet Loss Inlet Loss Impeller Mismatching Impeller Friction Loss Blade Loading Loss	0.01 0.37 0.01 0.00	0.02 0.25 0.02 0.00	0.03 0.16 0.03	0.05 0.04 0.07	0.49 0.07 0.01 0.09	0.08 0.00 0.11	b <sub>2</sub> B.	12.1 26	mm °
D0 nominal         39.76         35           Hydraulic Eff.         77.69         %           Volumetric Eff.         96.75         %           Mechanical Eff.         97.0         %           Overall Eff.         72.91         %           Output Power         0.18         kW	i mm	C1 2.95 Cm1 2.00 D1 33.0 D1d 38.0	~ 3.09 m/s mm	m/s D2 u2 Cm2 Cu2	87.3 14.27 1.52	94 mm m/s m/s		Impeller Mismatching Impeller Friction Loss Blade Loading Loss	0.37	0.25 0.02 0.00	0.16	0.04	0.01	0.00	<u>β</u>	26	0
Hydraulic Eff. 77.69 % Volumetric Eff. 96.75 % Mechanical Eff. 97.0 % Overall Eff. 72.91 % Output Power 0.18 kW		Cm1 2.00 D1 33.0 D1d 38.0	m/s mm mm	u2 Cm2 Cu2	14.27 1.52	m/s m/s		Impeller Friction Loss Blade Loading Loss	0.01	0.02	0.03	0.07	0.09	0.11	ß.	26	o
Volumetric Eff. 96.75 % Mechanical Eff. 97.0 % Overall Eff. 72.91 % Output Power 0.18 kW		D1 33.0 D1d 38.0	mm	Cm2 Cu2	1.52	m/s		Blade Loading Loss	0.00	0.00	0.00			0.00		20	
Mechanical Eff. 97.0 % Overall Eff. 72.91 % Output Power 0.18 kW		D1d 38.0	mm	Cu2	7.06	mle					0.00	0.00	0.00	0.00	P1		
Overall Eff.         72.91         %           Output Power         0.18         kW				www.fie	1.50	111/5		Volute Mismatching	4.67	4.40	4.14	3.64	3.40	3.17	ß	20	o
Output Power 0.18 kW		D1i 28.0	mm	Hmax	10.39	m		Volute Friction Loss	0.63	1.11	1.74	3.41	4.46	5.64	P <sub>2</sub>	50	
Output Power 0.18 kW		u1 5.01			10.05	•		TOTAL HEAD	10.48	9.79	9.05	7.18	6.01	4.66		-	
		u1d 5.77		p2-0	15.0	° 40.7					1. Harden e		172241417		Z	5	-
Input Power 0.24 kW		010 5.77		pz	38	40.7		16									
Torque 0.80 Nm	_	u1i 4.25	m/s	Z	5	7.2		14 Theoretic	al Head	1 • • •					e	3	mm
Dshaft 6.97 12	mm	β1-0 21.8	<b>.</b>	e	3	mm		12									
Dhub 17.0 mm		β1 26	<mark>_</mark> .	λ2	0.92			E Actu	al Hea	d					n	2900	rpm
Calculate		β1d 23.2	<u> </u>	b2	5.01	12.1 mm		10		-	-						
Losses		β1i 29.2	-	angle b2/b1	24.0	11		± 8							Q	120	l/min
		b1 15.3	mm	λ1	0.67			i 6	_								
				b1	14.85	17.5 mm		Total He	d Loss								

20

180 200

160

120

Flow Rate l/min

0

### Results and Discussion CFD Results

Approximately 450 iterations were run to reach the convergence criteria of residuals.

Residual type of RMS (root mean square) is selected.



### Results and Discussion CFD Results – Pump-1



Flow rate	ΔΡ	Н
(l/min)	(bar)	(m)
390	2.03	20.71
600	1.82	18.56
850	1.1	11.22



### Results and Discussion CFD Results – Pump-2



Flow rate (I/min)	ΔP (bar)	H (m)
150	1.03	10.51
300	0.86	8.77
450	0.64	6.53



### Results and Discussion CFD Results – Pump-3



Flow rate (I/min)	ΔP (bar)	H (m)	
60	0.96	9.79	
120	0.73	7.46	
180	0.43	4.39	

### Results and Discussion Comparison of Results – Pump-1



### Results and Discussion Comparison of Results – Pump-2



### Results and Discussion Comparison of Results – Pump-3



### Results and Discussion Comparison of Results

	Q	Prediction	Performance	CFD
	(l/min)	(m)	(m)	(m)
	390	21.05	20.9	20.71
Pump-1	600	17.03	15.85	18.56
	850	8.90	6.51	11.22
Pump-2	150	13.04	11.53	10.51
	300	9.52	8.99	8.77
	450	3.09	4.07	6.53
Pump-3	60	10.48	9.78	9.79
	120	7.92	7.9	7.46
	180	4.66	5.46	4.39

### Results and Discussion Comparison of Results

The performance predictions are compared with CFD calculations and experimental measurements of the same pump geometry.

- □ The performance tool has the advantage of less effort and time spent compare to CFD analysis.
- Predictions showed that the volute design has a significant effect on the pump performance.

Characteristics of three different pumps using loss correlations are in good agreement with performance curves at BEP and offdesign points of the pumps with specific speed range between 40 to 180. Therefore, the developed performance prediction code is highly reliable and consistent.

### Results and Discussion Future Work

There are certain options would be added to the prediction software such as

Material Library

Trapezoidal section for volute calculations

Save project

Export blade profile

Printing H-Q curve

# Thank You for Listening