Churning Losses Evaluation On A Swashplate Axial Piston Pump Using Moving Particle Approach

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[1] DMSI S.r.l. – FP Division [2] EnginSoft S.p.a.

People Finding A Better Way®

Dana Snapshot

Founded in **1904**

2018 sales:
$8.1 billion

~36,000
people

25
technical
centers

145 major facilities

33 countries

6 continents

~15,000 customers in

141 countries

Business Overview

Markets

Light Vehicles

57%

Heavy Vehicles

21%

Off-Highway

23%

Segments

Light Vehicle Driveline Technologies

44%

Commercial Vehicle Driveline Technologies

20%

Off-Highway Drive and Motion Technologies

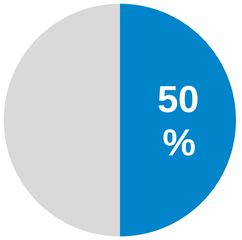
23%

Power Technologies

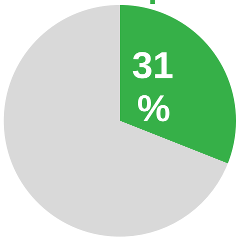
14%

Regions

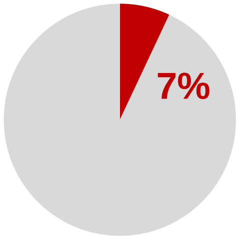
North America



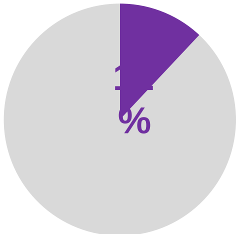
Europe



South America



Asia Pacific



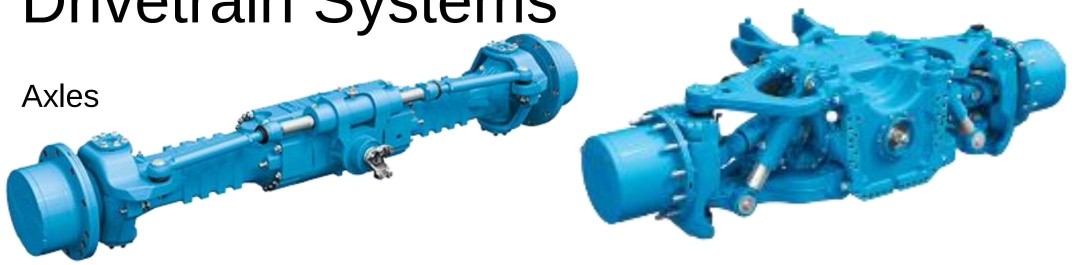
Technologies	Products
Drive	Axles, driveshafts, transmissions, hydraulic wheel and track drives, drive units for electric and hybrid vehicles
Motion	Winches, slew drives, planetary gearboxes, hydraulic pumps, motors and valves, electronic controls
Electrodynamic	E-Motors, generators, power electronics, controls and software
Thermal	Transmission and engine oil cooling, battery and electronics cooling, charge air cooling, and exhaust-gas and heat recovery
Sealing	Gaskets and seals, transmission separator plates, cam covers and oil pan modules, heat shields, and fuel cell plates
Digital	Active and passive system controls, Software as a Service including descriptive and predictive analytics

Sales as of Dec. 31, 2018. Consolidated sales only.

Off-Highway Extended Product Portfolio

Drivetrain Systems

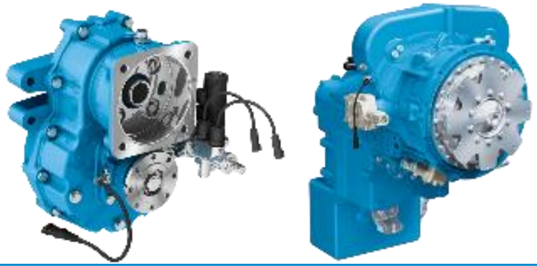
Axles



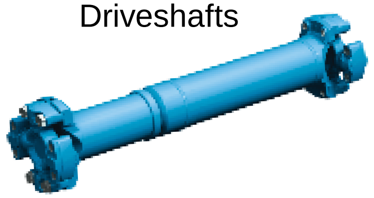
Wheel Drives

Track Drives

Transmissions

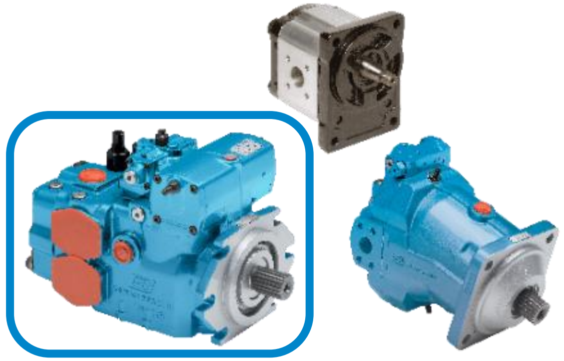


Driveshafts



Motion Systems

Planetary
Gearboxes
Industrial



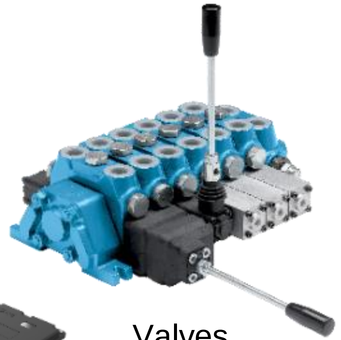
Motors & Pumps

Bevel Helical Gearboxes

Pump drives /
splitter boxes

Winches

Electronic Controls

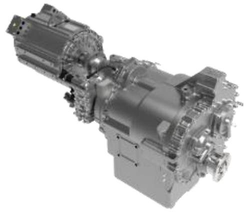


Valves
and Flow Control

Power
packs

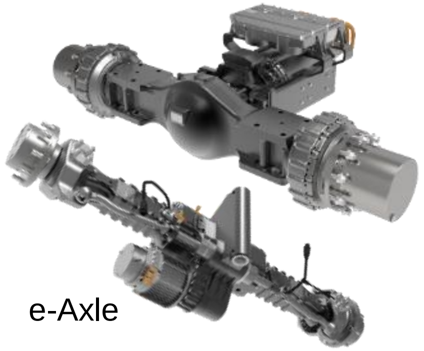
Industrial Shafts

Electrification



e-Transmissions

e-Hub Drives



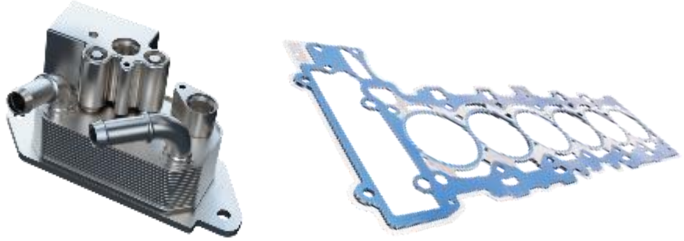
e-Axle

e-Gear Pump

e-Slew Drive

Gears and Components

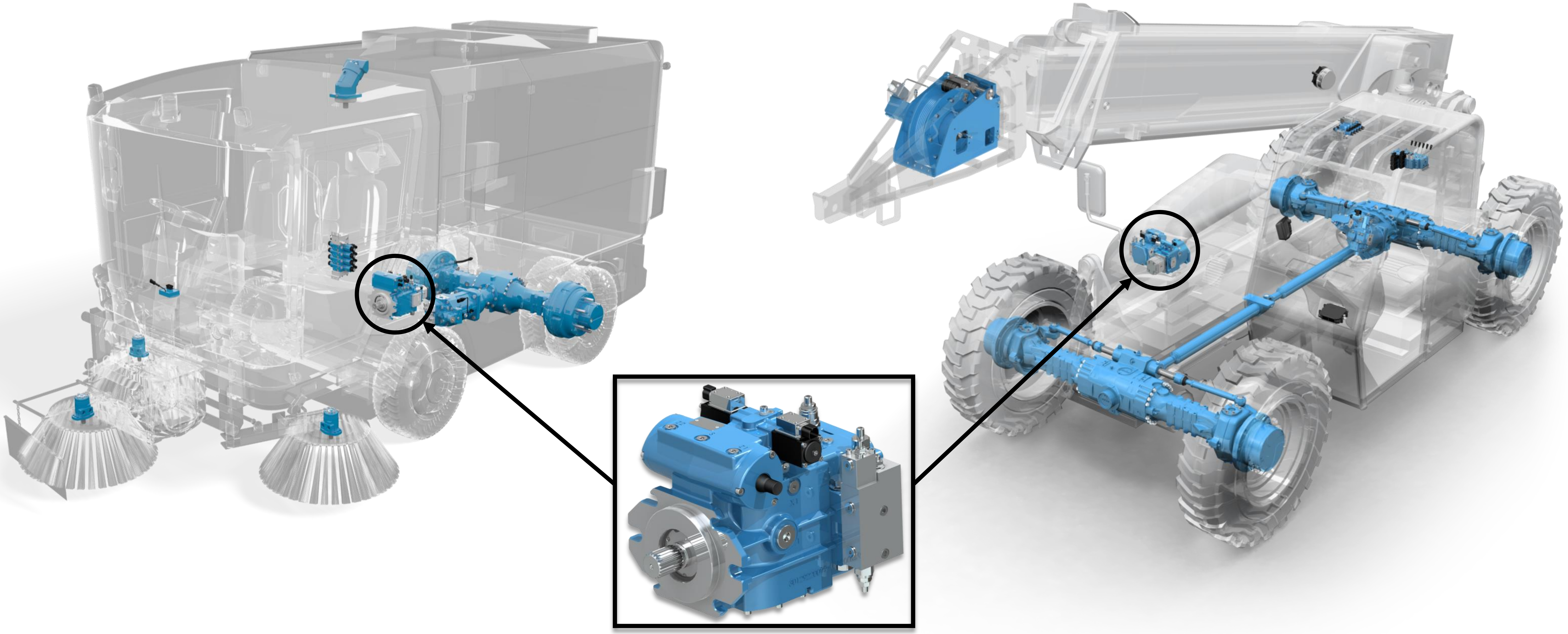
Thermal-Management and Sealing



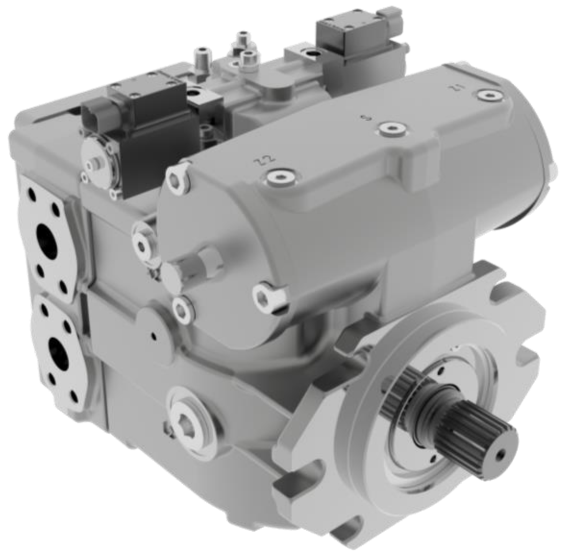
Possible Off-Highway Solutions

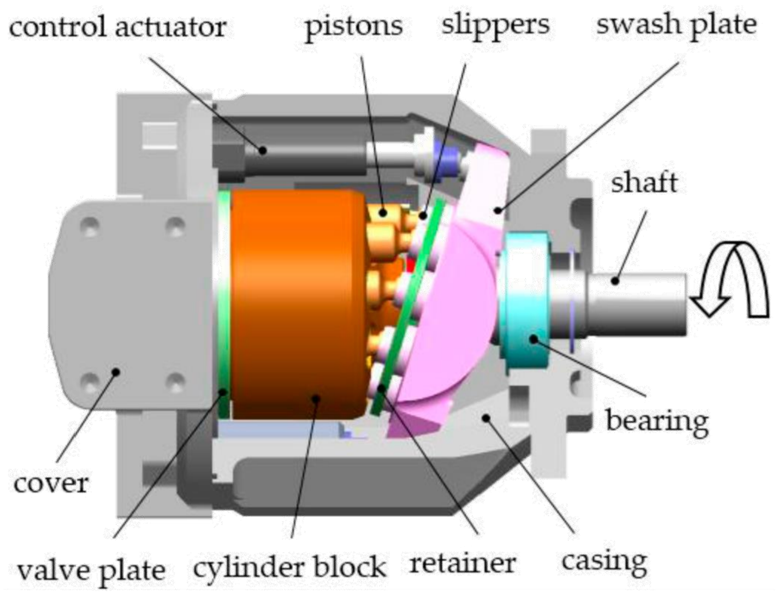
Road sweeper

Telehandler



Axial Piston Pump





[*]

Widely used in fluid power systems because:

High power-mass ratio

High limit load pressure

High overall efficiency η_o

$\eta_o \uparrow \longrightarrow$ Vehicle Performance $\uparrow$

$$\eta_o = \eta_o(\eta_V; \eta_{hm})$$

η_V: volumetric efficiency

η_{hm}: hydro-mechanical efficiency

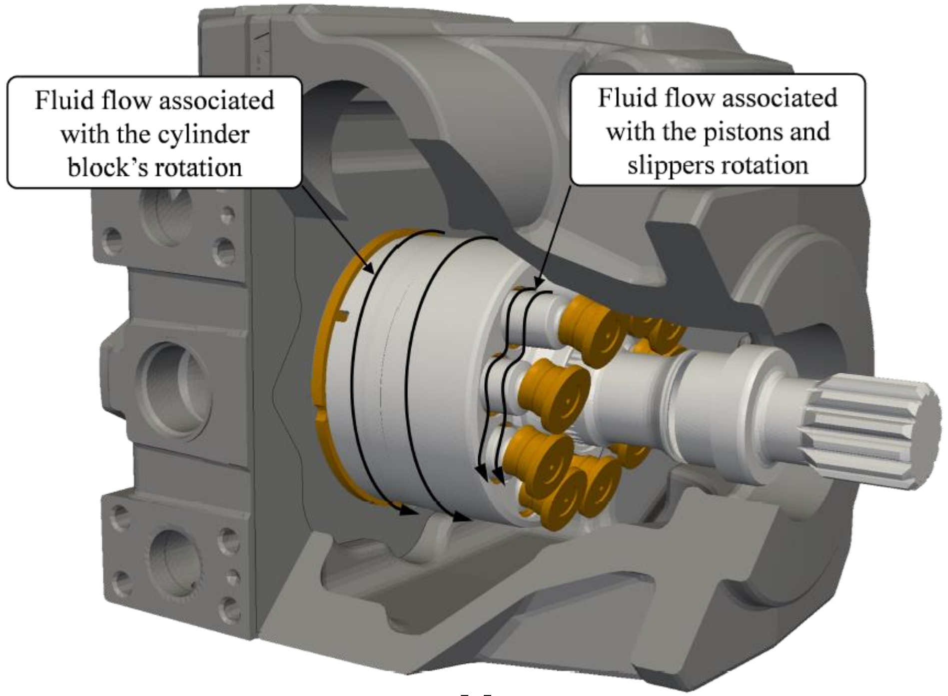
- Friction in lubricating interfaces
- Fluid drag
- Losses in shaft bearing & seals
- Churning losses

[*]: image from "Experimental study on the influence of the rotating cylinder block and pistons on churning losses in axial piston pumps", J.Zhang, Y.Li, B.Xu, M.Pan, F.Lv, State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Zheda Road 38, Hangzhou 310027, China

Churning Losses Approaches

CHURNING LOSSES ⟷ $P_{cl} = T_{cl} \cdot \omega$

Major contributions
- **CYLINDER BLOCK**
- **PISTONS**



[*]

Considered approaches:

1. Theoretical
2. Experimental

→ **LITERATURE**

3. CFD meshless → Particleworks — Particle-based simulation software for CAE

LITERATURE:

1. "A NOVEL APPROACH TO PREDICT THE STEADY STATE TEMPERATURE IN PORTS AND CASE OF SWASHPLATE TYPE AXIAL PISTON MACHINES"
2. "EXPERIMENTAL STUDY ON THE INFLUENCE OF THE ROTATING CYLINDER BLOCK AND PISTONS ON CHURNING LOSSES IN AXIAL PISTON PUMPS"

[*]: image from "A novel approach to predict the steady state temperature in ports and case of swashplate type axial piston machines", M.Zecchi, A.Mehdizadeh, M.Ivantysynova, Maha Fluid Power Research Center, Pordue University, 1500 Kepner Dr. Lafayette, IN, USA 47905

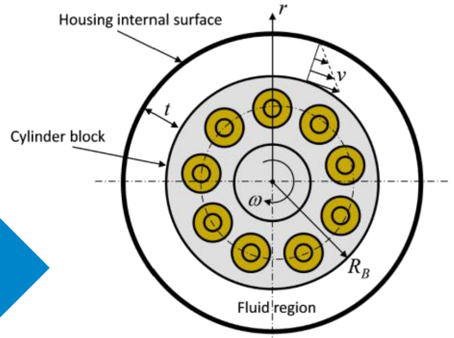
Theoretical & Experimental

THEORETICAL

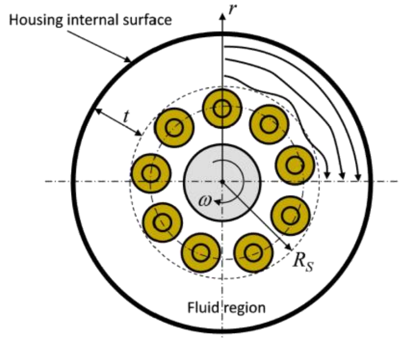
“A NOVEL APPROACH TO PREDICT THE STEADY STATE TEMPERATURE IN PORTS AND CASE OF SWASHPLATE TYPE AXIAL PISTON MACHINES”

M.Zecchi, A.Mehdizadeh, M.Ivantysynova

Maha Fluid Power Research Center, Pordue University, 1500 Kepner Dr. Lafayette, IN, USA 47905



CYLINDER BLOCK



PISTONS

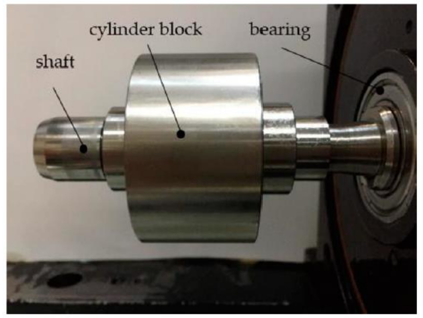
No 3D effects   High time & cost

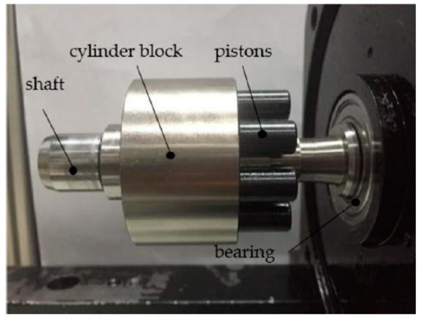
EXPERIMENTAL

“EXPERIMENTAL STUDY ON THE INFLUENCE OF THE ROTATING CYLINDER BLOCK AND PISTONS ON CHURNING LOSSES IN AXIAL PISTON PUMPS”

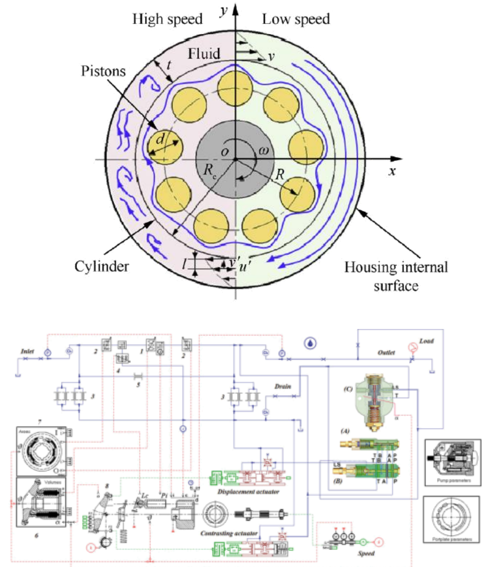
J.Zhang, Y.Li, B.Xu, M.Pan, F.Lv

State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Zheda Road 38, Hangzhou 310027, China

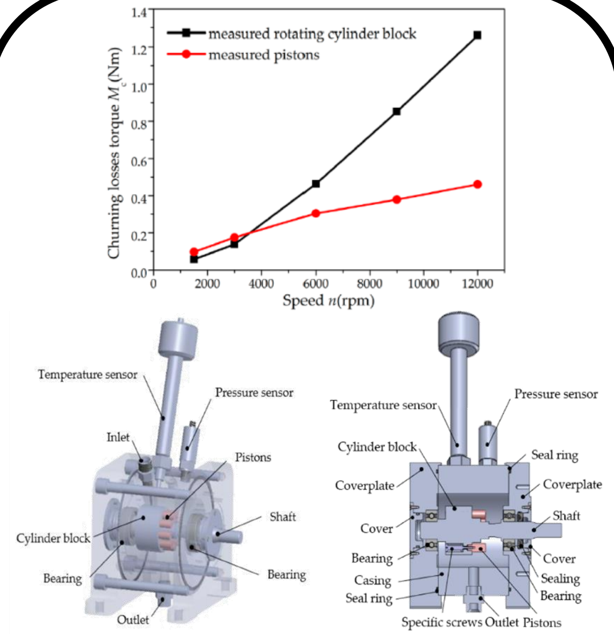




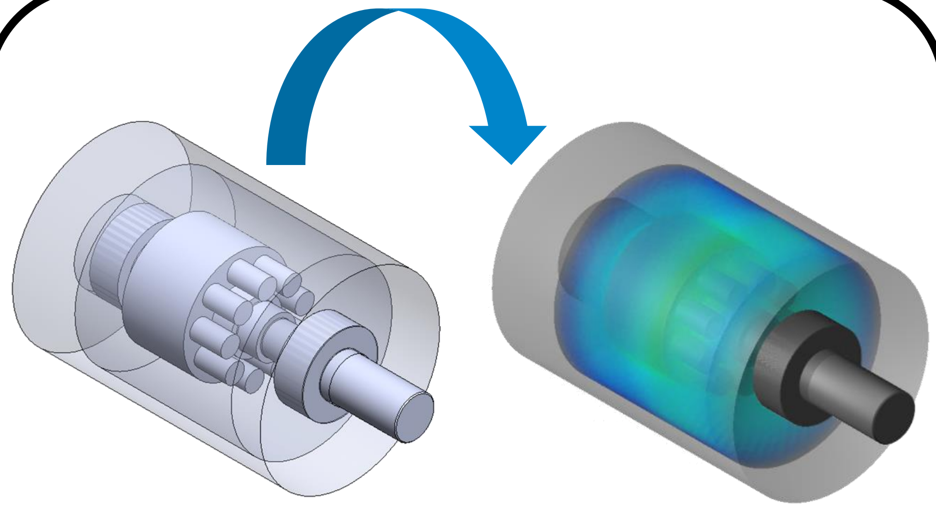
CFD Meshless – Followed Workflow



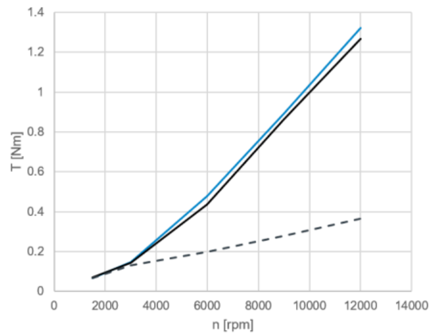
LITERTURE THEORETICAL APPROACH



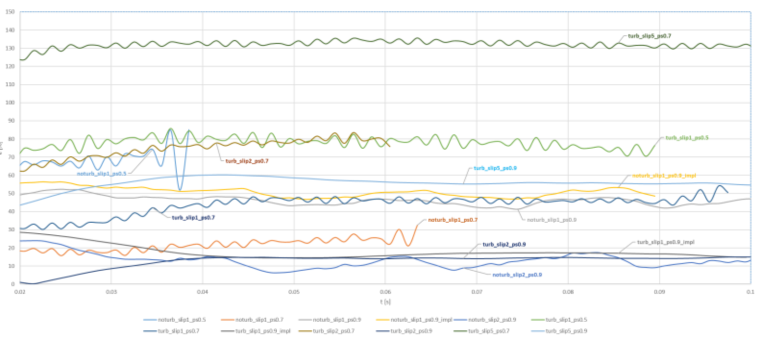
LITERATURE EXPERIMENTAL DATA



PARTICLEWORKS® MODEL



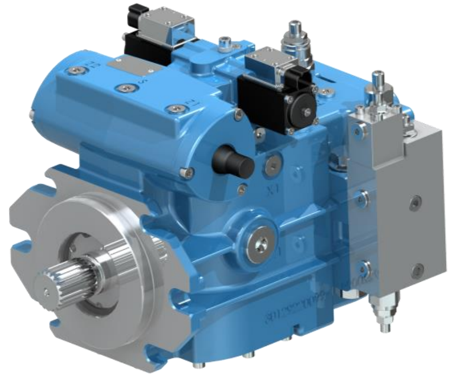
PARTICLEWORKS® MATCH EXPERIMENTAL DATA



PARTICLEWORKS® PARAMETERS SENSITIVE ANALYSIS

0 rpm ≤ n ≤ 3000 rpm

THEORETICAL APPROACH ≈ PARTICLEWORKS®



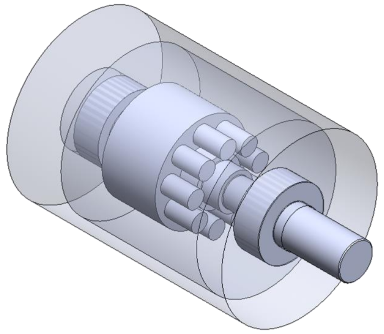
PARTICLEWORKS® ON DANA HD1 PUMP

CFD Meshless – Data Analysis

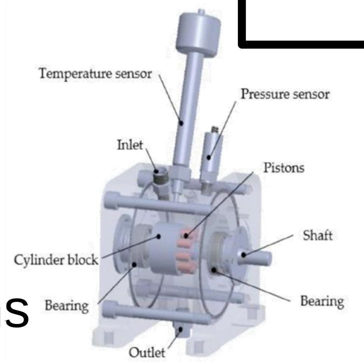
Geometry & Physic Parameters*

Parameters	Symbol	Value	Units
Number of pistons	z	9	-
Piston diameter	d	0.01	m
Pitch circle radius of piston bores	R	0.02	m
Radius of cylinder block	R_c	0.028	m
Length of the piston out of the cylinder block at the outer dead point	l_0	0.0165	m
Length of the cylinder block	l_c	0.0325	m
Gap between the cylinder block and the housing internal surface	t	0.0145	m

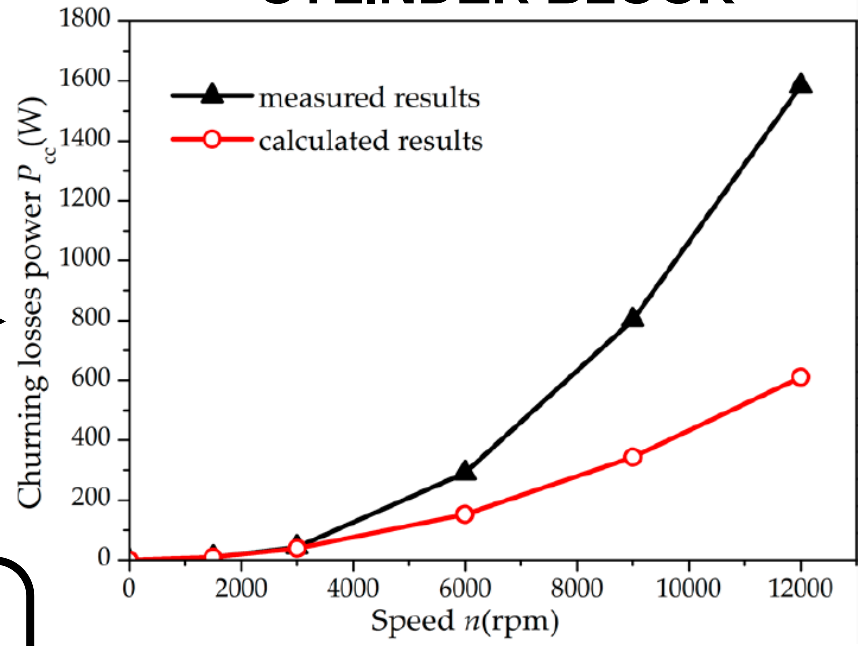
Parameters	Symbol	Value	Units
Test speeds	n	1500/3000/6000/9000/12000	rpm
Test temperature	T	35	°C
Test pressure	p	1.02	bar
Dynamic viscosity	μ	0.0278	Pa s
Density of test fluid	ρ	850	kg/m^3



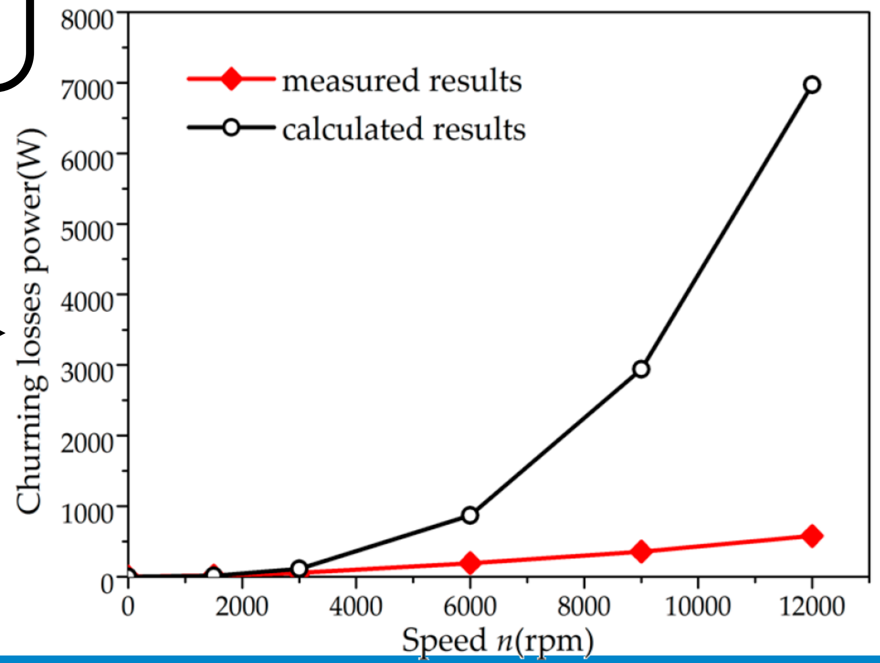
THEORETICAL & EXPERIMENTAL APPROACHES*



CYLINDER BLOCK



PISTONS



* Data & graphs available from previous literature documentations

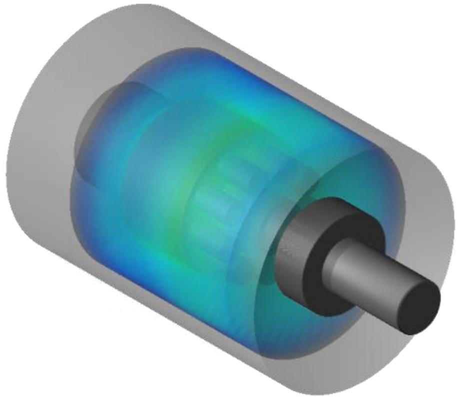
CFD Meshless – Model Set Up

Particleworks® Parameters

Parameters	Symbol	Value	Units
Particle size	*PS*	0.60	mm
Auto grid interval	-	On	-
Flow resistance res.	-	0.50	-
Slip factor	*SF*	From 3 to 5	-
Contact angle	*CA*	25	deg
Pressure	*Type*	Explicit	-
	Mode	Stabilized	-
	Speed of sound	100	m/s
Viscosity	*Type*	Explicit	-
Surface tension	*Type*	Potential	-
Turbulence	*Type*	None	-
Finish time	*t*	0.25	s
initial dt	*Δt*	From $1e^{-5}$ to $2.5e^{-6}$	s
Courant number	-	0.2	-

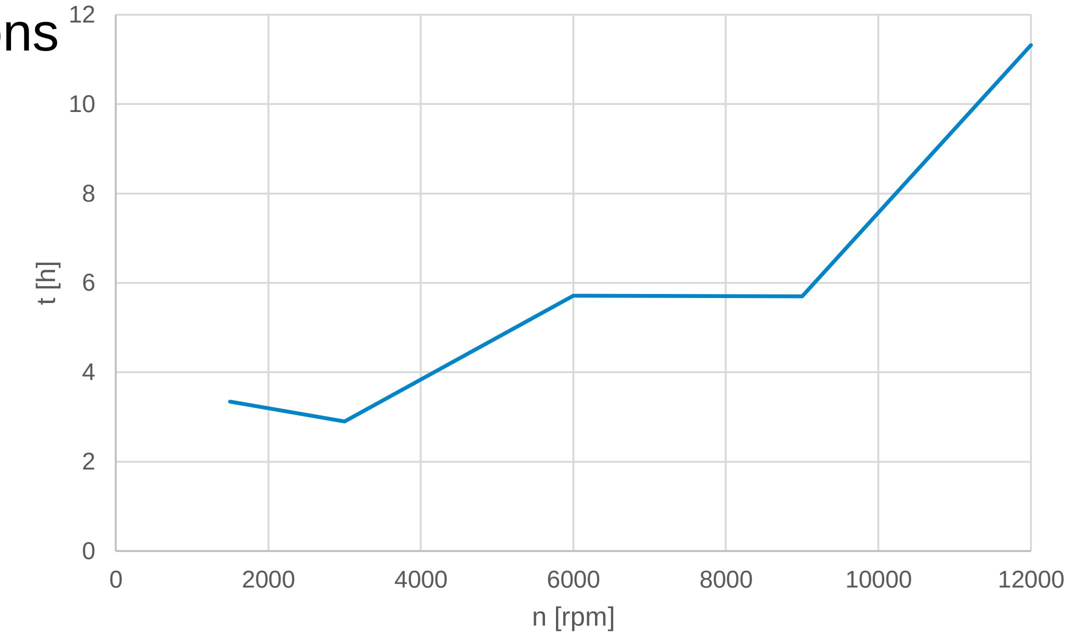
Number of particles:

1709296



Data from cylinder block simulations

t FOR 0.1 s OF SIMULATION		
n	t	t
[rpm]	[s]	[h]
1500	12031.50	3.34
3000	10452.90	2.90
6000	20565.80	5.71
9000	20506.90	5.69
12000	40735.60	11.31



From 3 hours to 11 hours of simulation

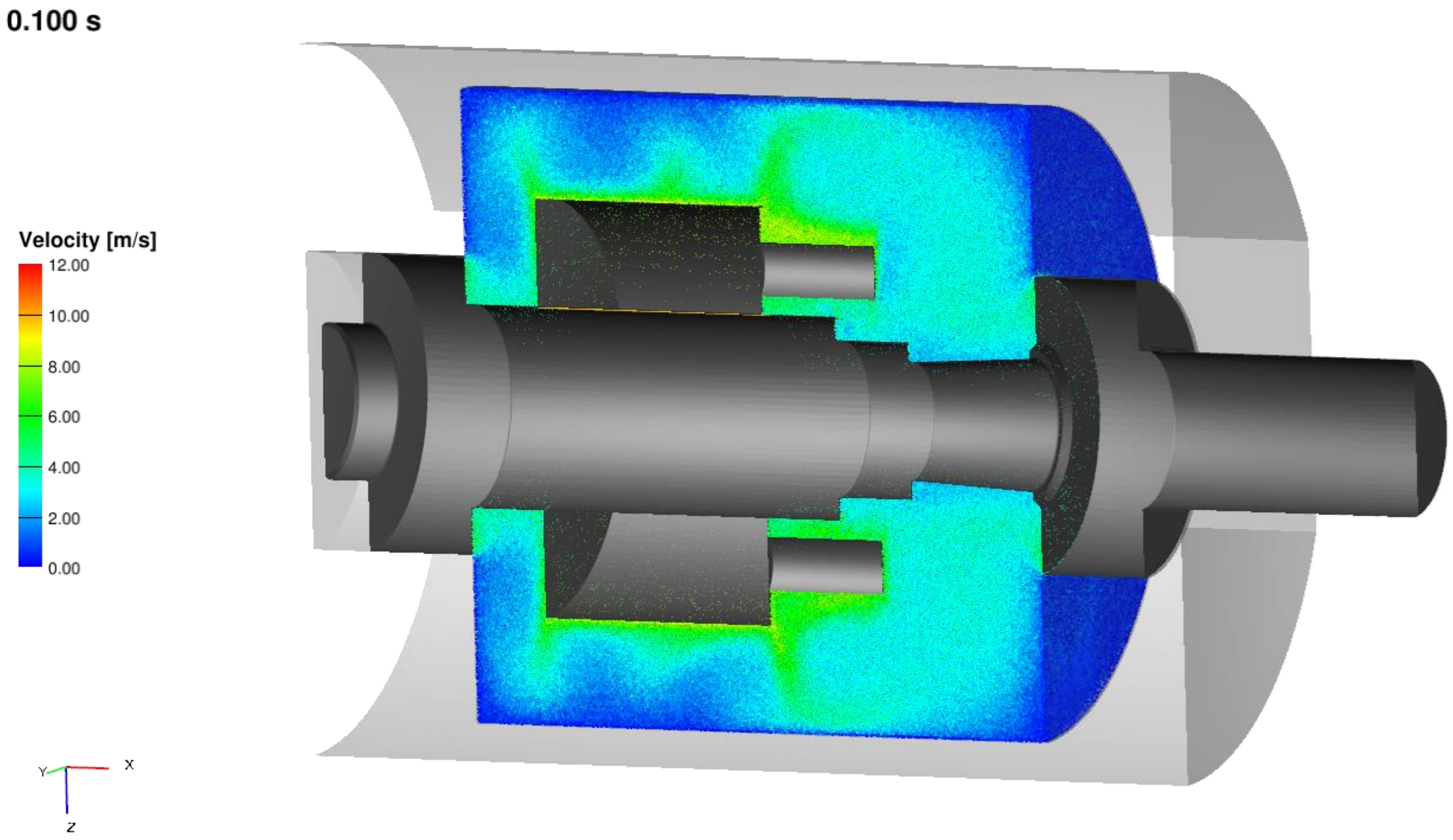
WORKSTATION SPECS:

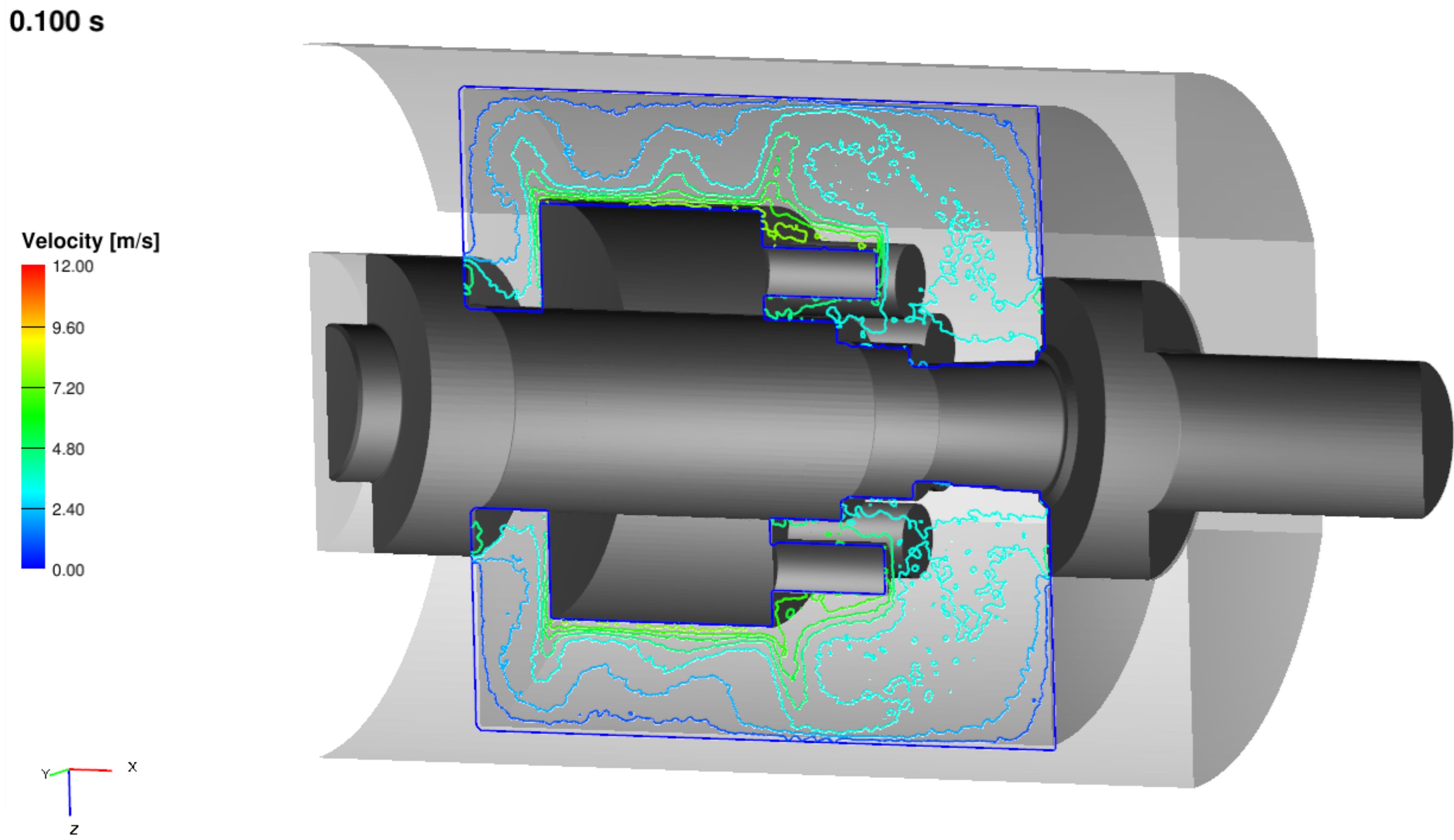
- PROCESSOR: Double processor IntelR XeonR E5-2660 v3 (10C, 2,6 GHz, 25 MB, 105 W)
- GRAPHIC: NVIDIA QuadroR M4000 - 8 GB (4 DP)
- MEMORY: RDIMM DDR4 ECC - 256 GB (8 x 32 GB) @ 2.400MHz

CFD Meshless - Images

n = 3000 rpm

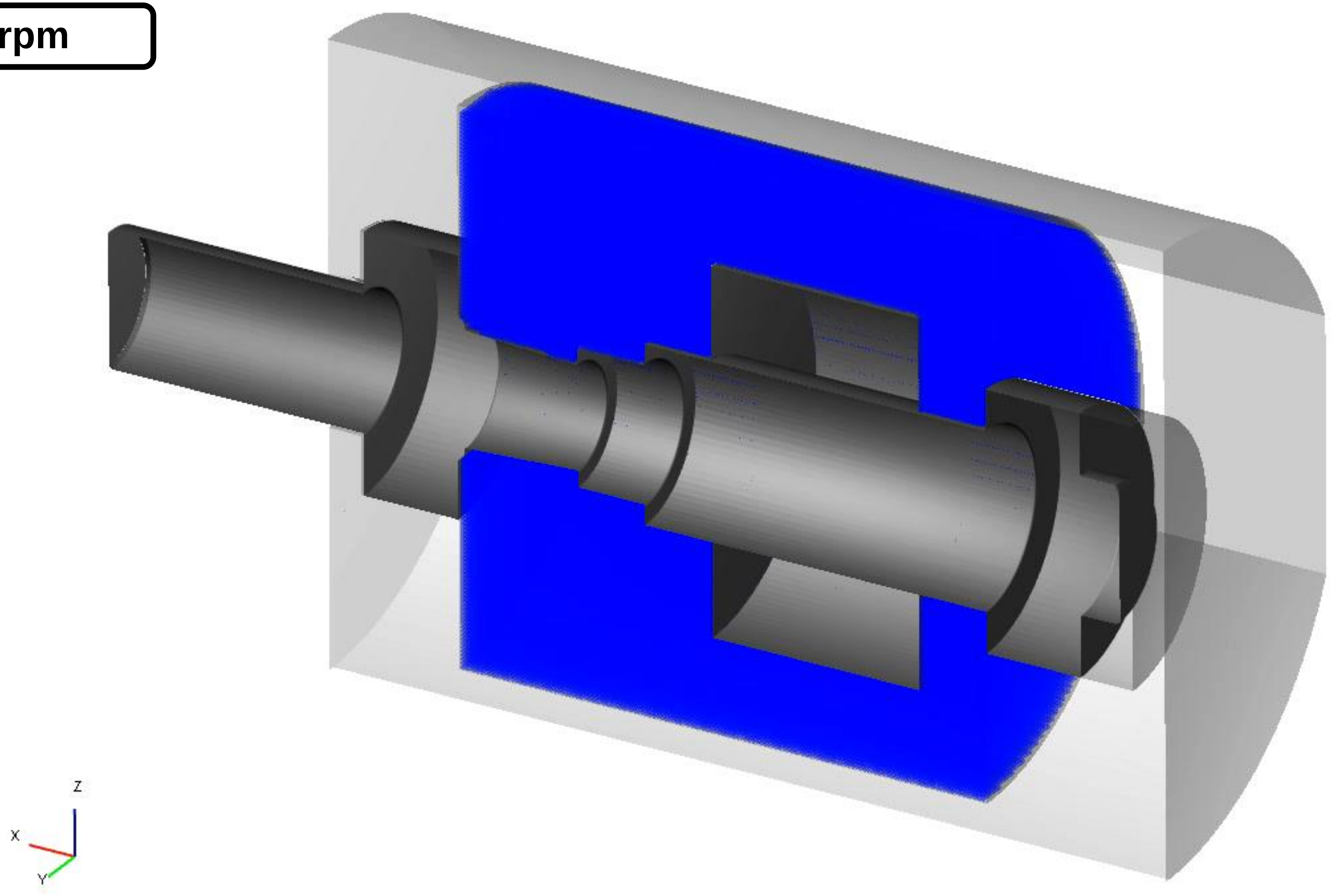
CYLINDER BLOCK





CFD Meshless - Video

n = 3000 rpm



CFD Meshless – Results Analysis

n = 3000 rpm

CYLINDER BLOCK

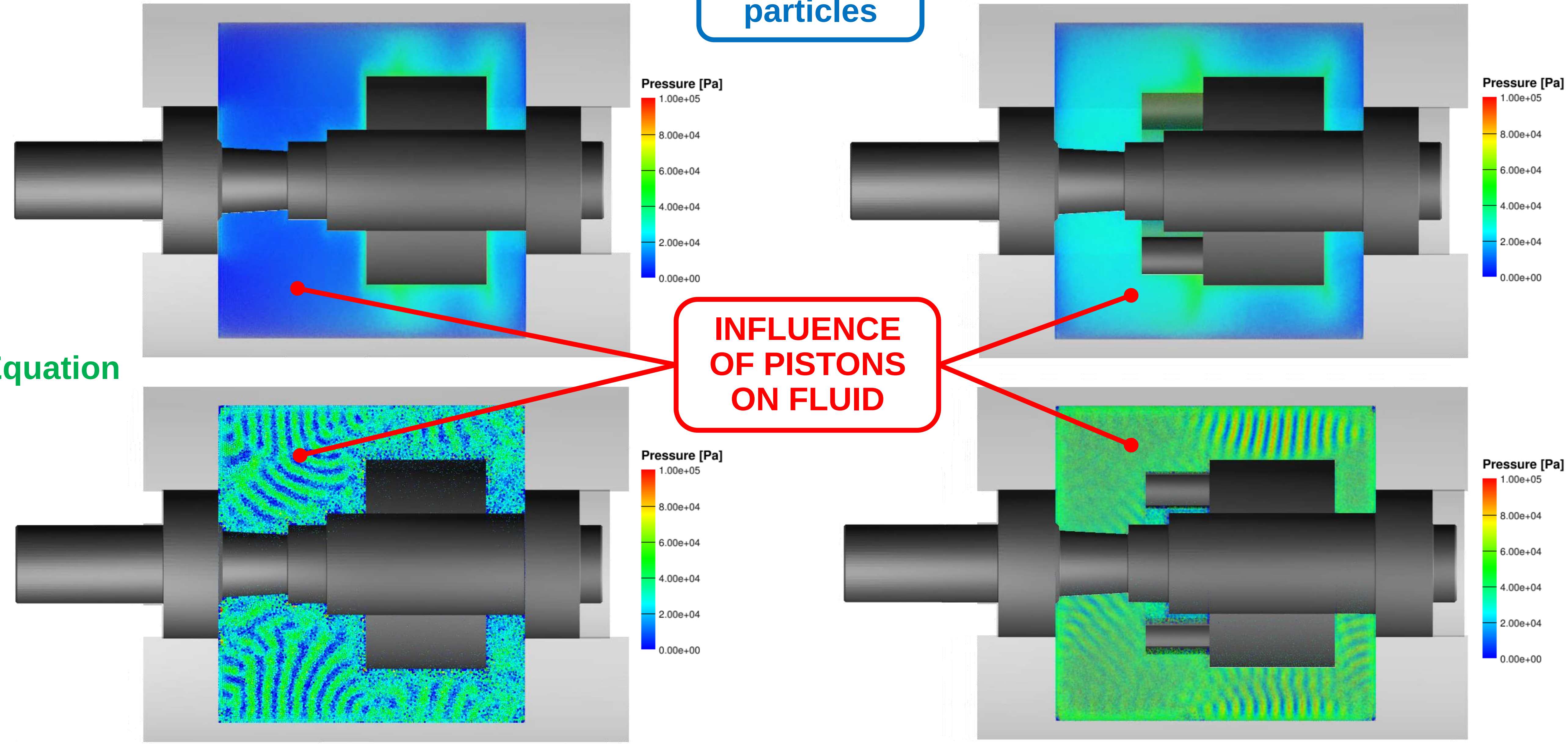
Case full of particles

PISTONS

Velocity

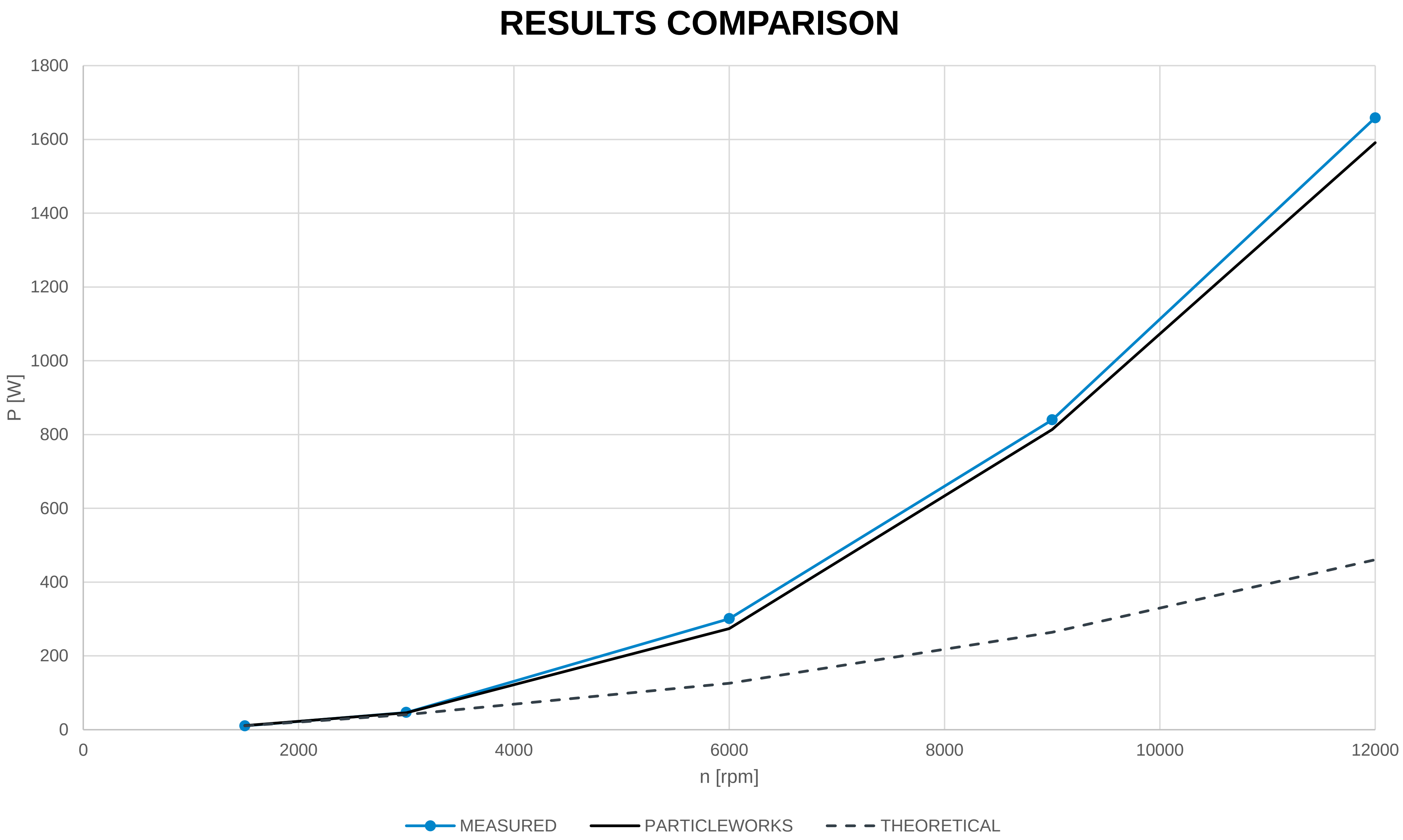
Navier-Stokes Equation

Pressure



CFD Meshless – Results Compare

CYLINDER BLOCK

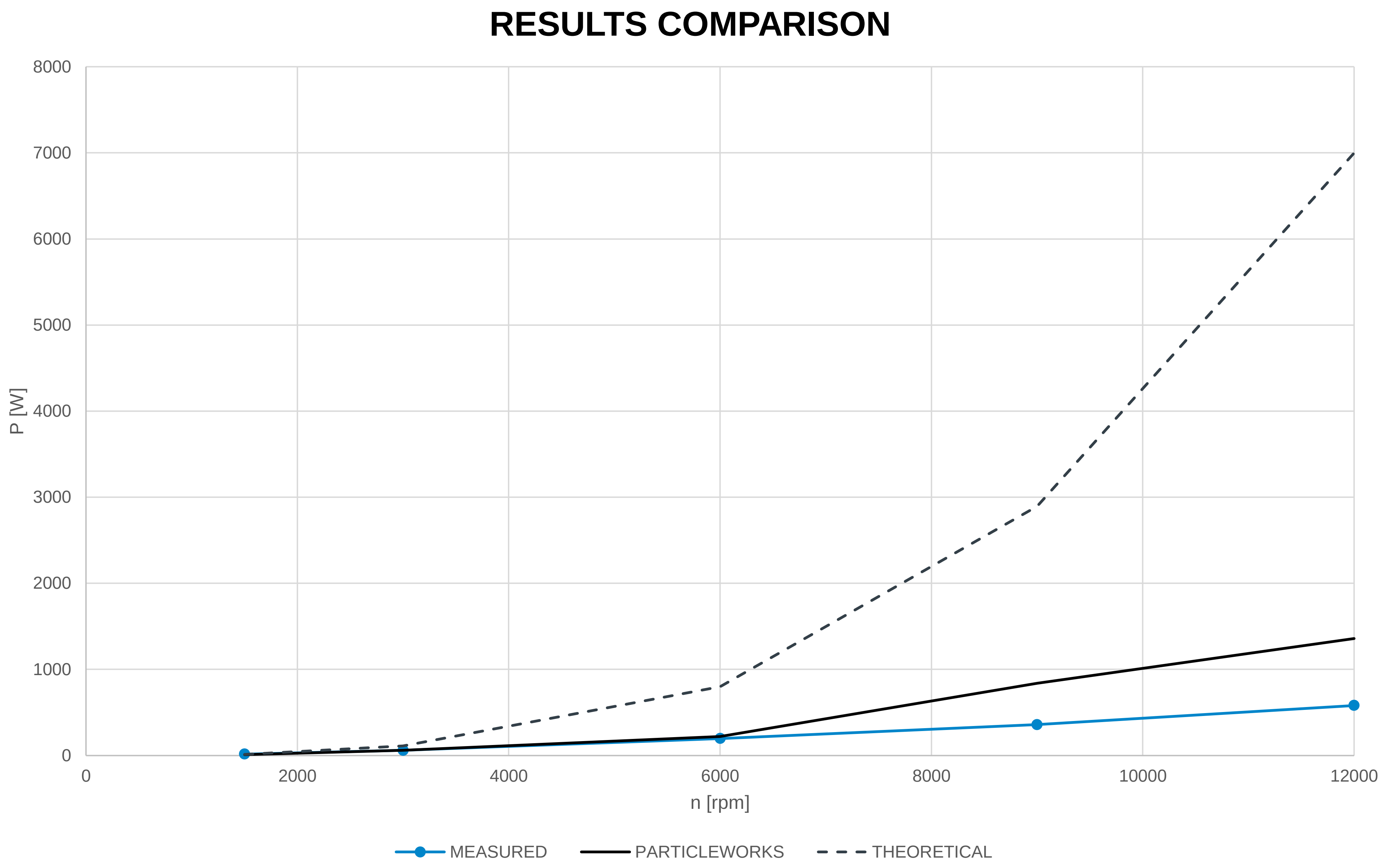


	MEASURED	PARTICLEWORKS	THEORETICAL
n	P	P	P
[rpm]	[W]	[W]	[W]
1500	10.37	11.22	10.48
3000	46.65	45.64	40.84
6000	300.65	273.91	125.66
9000	839.75	813.22	263.89
12000	1658.76	1591.08	460.77

	ERROR MEASURED-PARTICLEWORKS	ERROR MEASURED-THEROETICAL	ERROR PARTICLEWORKS-THEORETICAL
n	ε	ε	ε
[rpm]	[%]	[%]	[%]
1500	8.20	1.06	6.59
3000	2.18	12.46	10.51
6000	8.89	58.20	54.12
9000	3.16	68.57	67.55
12000	4.08	72.22	71.04

CFD Meshless – Results Compare

PISTONS



	MEASURED	PARTICLEWORKS	THEORETICAL
n	P	P	P
[rpm]	[W]	[W]	[W]
1500	15.55	10.21	12.88
3000	59.61	59.06	111.84
6000	196.98	219.91	797.96
9000	357.67	838.81	2893.41
12000	580.57	1357.17	6999.47

	ERROR MEASURED-PARTICLEWORKS	ERROR MEASURED-THEORETICAL	ERROR PARTICLEWORKS-THEORETICAL
n	ε	ε	ε
[rpm]	[%]	[%]	[%]
1500	34.34	17.17	26.15
3000	0.92	87.62	89.36
6000	11.64	305.10	262.86
9000	134.52	708.96	244.94
12000	133.77	1105.63	415.74

CFD Meshless – Parameters Assumptions

AIM: find a relation between Particleworks® particle size (PS) VS characteristic dimensions

$$\frac{PS_1}{l_1} = k = const$$

l_1: *characteristic dimension*

For similar geometry

$$PS_2 = k \cdot l_2, l_1 \neq l_2$$

For similar geometrical family:

$$PS_1 = k \cdot l_1$$
$$PS_2 = k \cdot l_2$$
$$\vdots$$
$$PS_n = k \cdot l_n$$

$$\boxed{PS_{opti\_fam} = min(PS_1; PS_2; \dots; PS_n)}$$

Following the fatigue limit theory:

$$\sigma_{lim} = k_A \cdot k_B \cdot k_C \cdot k_D \cdot k_E \cdot k_F \cdot \sigma_{SU}$$

Ideal PS for generic geometry:

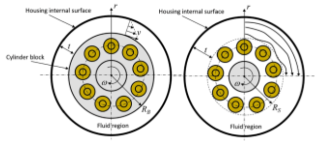
$$PS_{ideal} = \alpha_1 \cdot \alpha_2 \cdot \dots \cdot \alpha_n \cdot PS_{reference}$$

$\alpha_1; \alpha_2; \dots; \alpha_n$: corrective coefficients for geometry motion, physic, etc

$$\boxed{PS_{opti\_gen} = min(PS_{opti\_fam\_1}; PS_{opti\_fam\_2}; \dots; PS_{opti\_fam\_n})}$$

CFD Meshless – Dana HD1

0 rpm ≤ n ≤ 3000 rpm



THEORETICAL

CFD MPS

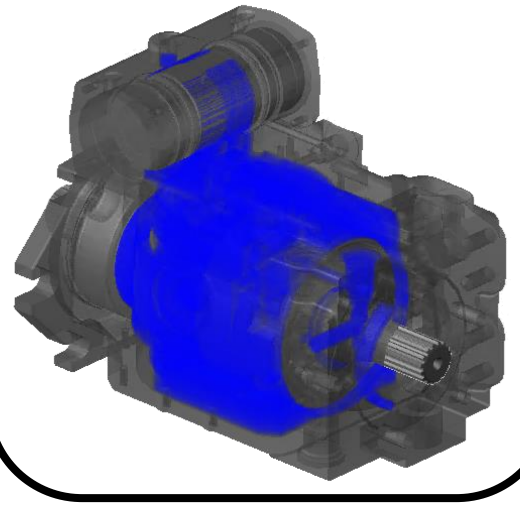
Typical range of usage

SIMULATIONS @ n* (fixed rotational speed)

	MEASURED	PARTICLEWORKS	THEORETICAL
n	P	P	P
[rpm]	[W]	[W]	[W]
1500	10.37	11.22	10.48
3000	46.65	45.64	40.84
6000	300.65	273.91	125.66
9000	839.75	813.22	263.89
12000	1658.76	1591.08	460.77

Churning losses evaluation using theoretical approach in n*

Particleworks® HD1 pump model IMPLEMENTATION



Particleworks® HD1 pump model matches theoretical approach

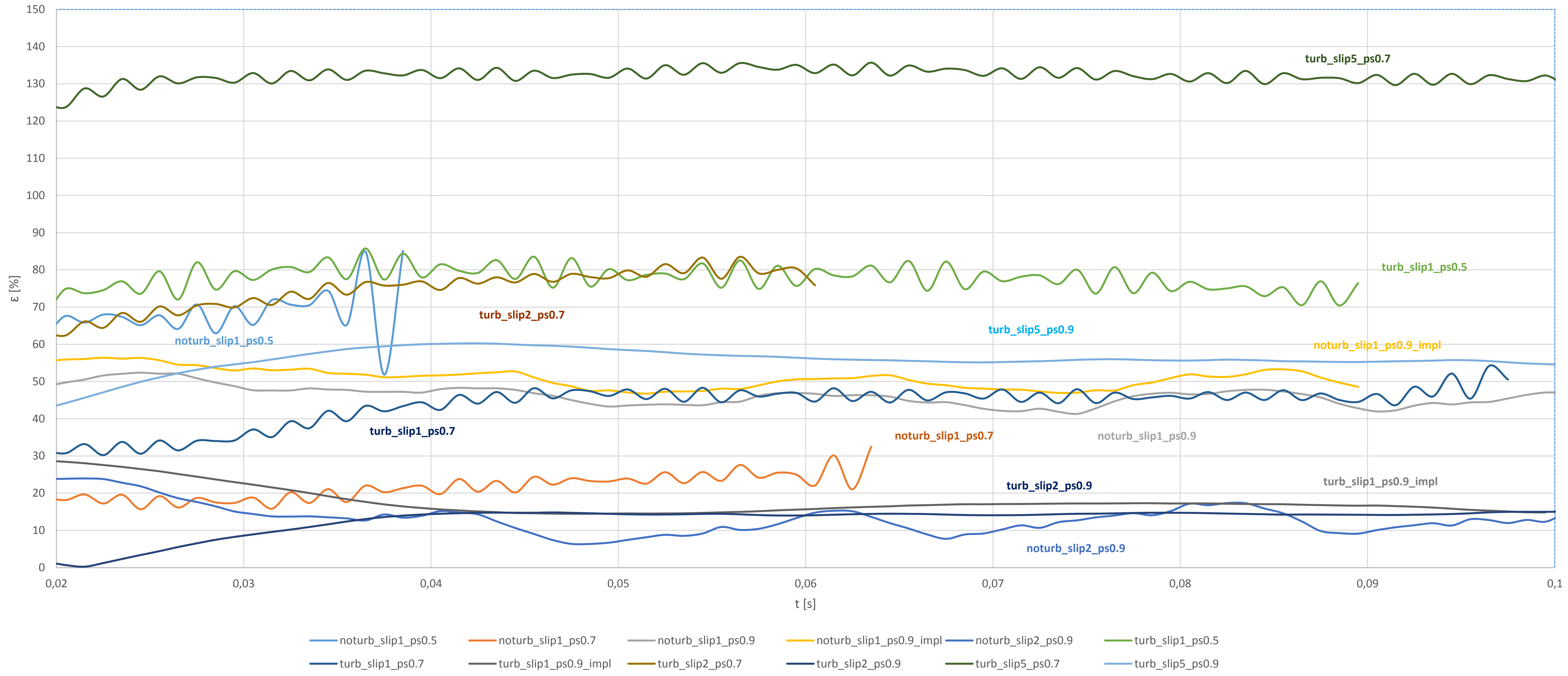
Particleworks® parameters SENSITIVITY:

- Particle size (PS)
- Slip factor (SF)
- Pressure solver
- Turbulence LES model

Simulation results:

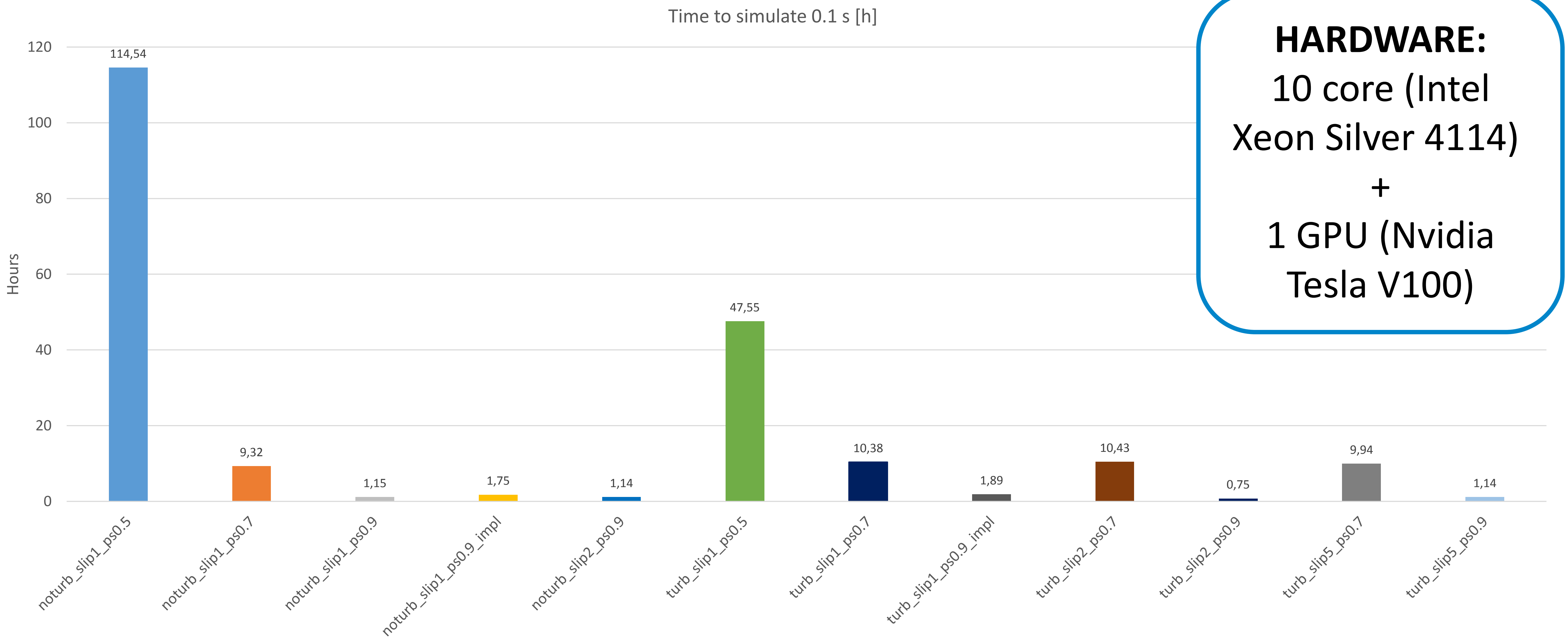
- Churning losses values
- Complex flow distribution
- Components surface mapping (pressure, velocity, forces & moments)
- Others

CFD Meshless – Sensitivity



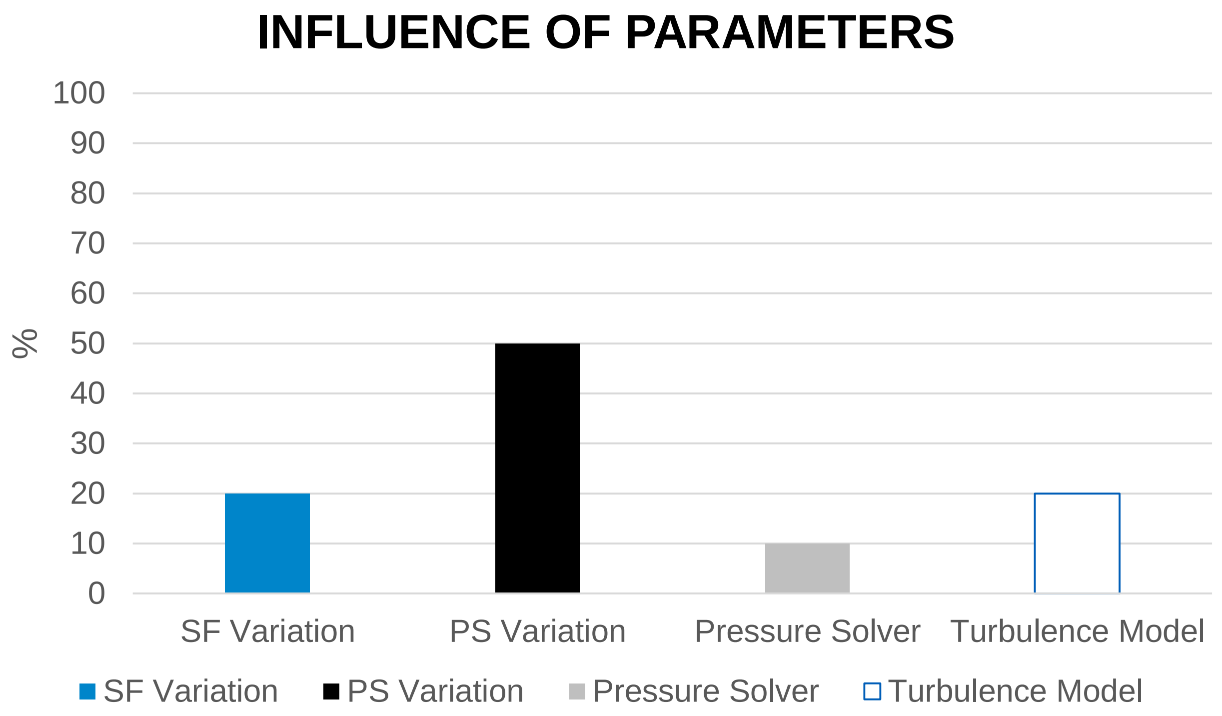
Benchmark with HD1 reference value

CFD Meshless – Sensitivity



HARDWARE:
10 core (Intel Xeon Silver 4114)
+
1 GPU (Nvidia Tesla V100)

CFD Meshless – Sensitivity Outcomes



1. **Pressure solver**

   Implicit ≈ Explicit → *Better fit incompressible fluid models*

2. **Particle size variation**

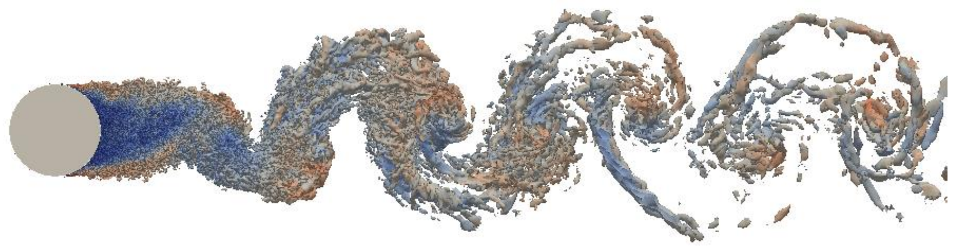
   ⬇ *Particle size* → ⬆ *Accuracy* & ⬆ *Time*

3. **Slip factor variation**

   ⬆ *Slip factor* → *Turbulence model switched OFF* → ⬇ *Time* & **?** *Accuracy (Need Tuning)*

4. **Turbulence model**

   Re > 2•10^5 → *Turbulence model ON* → ⬆ *Accuracy* & ⬆ *Time*



Conclusions & Next Steps

- **Conclusions**
  - New workflow tested in order to evaluate churning losses in axial piston pumps
  - Particleworks® aligned with experimental data
  - CFD meshless approach can be used to calculate churning losses in an axial piston pumps
  - Sensitivity analysis on Particleworks® parameters allowed computational time reduction with the same results
- **Next Steps**
  - Deeper analysis of LES turbulence models

DANA

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