Presentation

Measuring the losses of hydrostatic pumps and motors
A Critical Review of ISO4409:2007

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In the next 15 minutes, I will be talking to you about the way we measure and define losses of our hydrostatic pumps and motors.

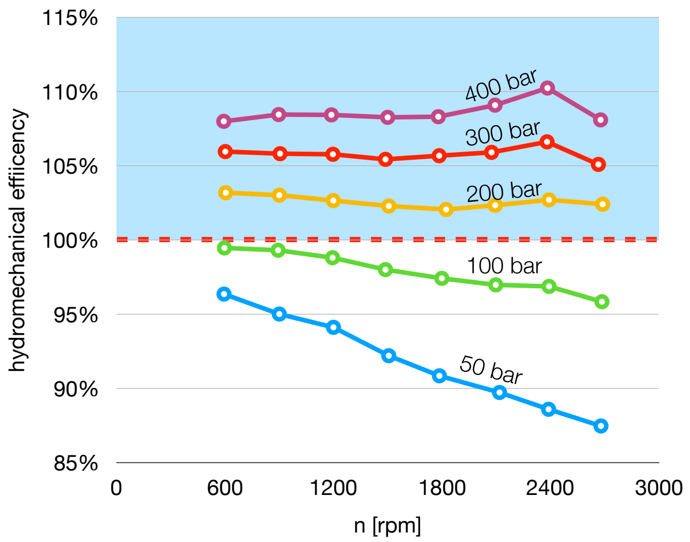
Actually, we hardly talk about losses: we talk about efficiencies:

- the overall efficiency,
- the hydromechanical efficiency
- and the volumetric efficiency.

These efficiencies and the way they are measured and determined are described in ISO 4409, and other similar and adjacent standards. In this presentation I am going to question these definitions.

But, let me first go back to a thesis that Niall Caldwell wrote in 2007.

Thesis Niall Caldwell 2007



- Test Digital Displacement Pump "C2"
- According to ANSI/NFPA T.3.9.17 (equivalent to ISO 4409)
- Hydromechanical efficiencies > 100% (up to 110%)

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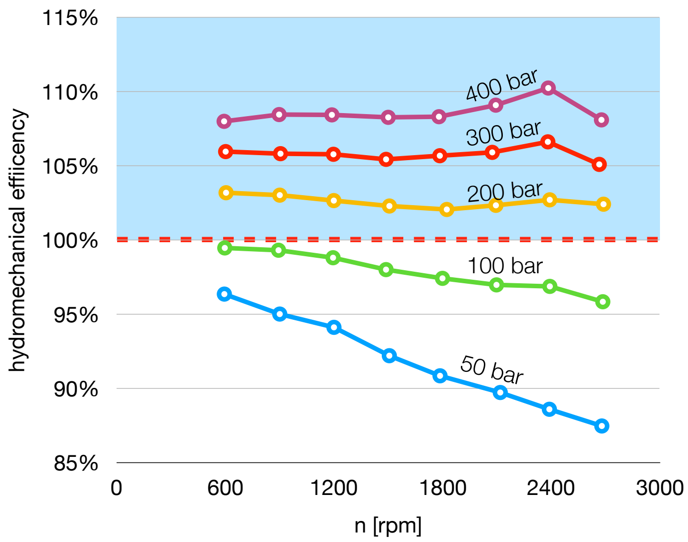
These were some of the test results, which Niall Caldwell presented in his thesis. It shows the hydromechanical efficiency of a pump at various pressure levels and rotational speeds.

It was a special pump: a prototype of the digital displacement pump developed by Artemis.

The measurements were performed according to the US standard, which is similar to ISO 4409.

Remarkable about these results is that, for a large part of the operation, the hydromechanical efficiency is above 100%.

Thesis Niall Caldwell 2007



- "clearly meaningless"
- Correction needed of the definition of the volumetric displacement:

$$V_{comp}(p) = V_{geom}\left(1 + \frac{V_{dead}}{V_{geom}}\right)\frac{p}{\beta}$$

dead volume

fluid bulk modulus

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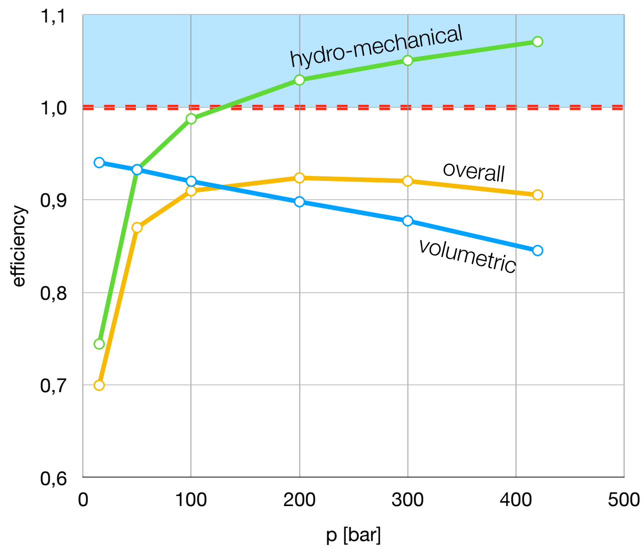
Niall concluded rightfully that these results are "clearly meaningless." However, there was nothing wrong with the measurements as such.

According to Niall Caldwell, the mistake was caused by the definition of the volumetric or geometrical displacement. In his thesis, he suggests that the conventional definition of the displacement volume needs to be corrected by a factor, which includes the dead volume of the pump and the bulk modulus.

Manring and Williamson (2018)



- test of a E-dyn® 96 digital displacement pump
- hydro-mechanical efficiency > 100%
- Correction needed of the definition of the volumetric displacement:

dead volume

$$V_p = \left[x - \left(x + \frac{V_{dead}}{\Delta V} \right) \frac{\Delta p}{\beta} \right] \frac{N \, \Delta V}{2\pi}$$

fluid bulk modulus

- for "check-valve type pumps" only

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In another study, which was presented last year, Noah Manring and Chris Williamson found a similar problem as Niall Caldwell did in 2007.

Measurements of a 96 cc digital displacement pump revealed that the hydro-mechanical efficiency could become higher than 100%.

Like Caldwell, they suggested a correction of the volumetric displacement.

They concluded that this correction is not only needed for digital displacement pumps, but for all pumps which are operated by means of check valves.

This presentation

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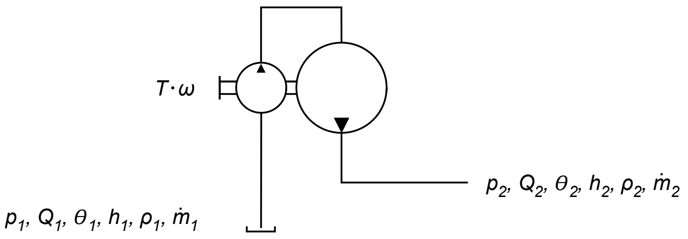
Are Caldwell, Manring and Williamson correct in their observations and suggestions? Or is there something —more fundamentally— wrong in the way we calculate and analyse the losses and efficiencies of hydrostatic pumps and motors?

This presentation

- Thermodynamic analysis of the bulk modulus effects on the energy efficiency and power loss definitions
- For all kinds of positive displacement pumps and motors
- A review of ISO 4409:2007

Previously ISO 4409:2007 › **Now** ISO 4409:2019

- ISO 4391, ISO 4392 1-3,…
- ANSI/NFPA T.3.9.17
- JIS B 8384-2011



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This is what we have investigated on the basis of a thermodynamic analysis.

We looked at all positive displacement pumps, not only at digital displacement pumps or check valve operated pumps. And we also included motors in our analysis.

The starting point for our investigation were the definitions used in ISO 4409, of which recently a new, revised version has been published.

ISO 4409 is also referring to, and being referred to in other international and national standards, and therefore our analysis and review also includes these standards.

The new ISO 4409 refers to ISO 4391 for the equations to calculate the various efficiencies. In this respect, this paper and presentation should be considered as a critical review of the relevant equations mentioned in ISO 4391.

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Standards are the cornerstone of our knowledge, and a review - certainly a critical review- should never be taken lightly.

Knowing this, we decided to discuss these matters in group of internationally acknowledged leaders of our community. They also became co-authors of this paper, and I have the honor to represent them here.

Furthermore, I want to mention that Robin Mommers of our company has also played an important role in the thermodynamic analysis and the evaluation of the test data.

Why?

- Can we define better equations for power losses and energy efficiencies?
  - Better: an improved understanding of the losses in pumps and motors
- Only discussion of the methodology, not of the instrumentation errors

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Our objective was to come with definitions and a methodology which would allow a better understanding of the losses in pumps and motors.

We are also aware that there are discussions going on about measurement errors due to instrumentation, for instance about a correct measurement of the flow rate.

However, this paper and this presentation is only about the methodology and not about possible instrumentation errors.

New equations for losses and efficiencies

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We can measure all sorts of parameters: torque, rotational speed, pressure levels, flow rates and temperatures. However, the power losses and efficiencies are not directly measured.

Instead these performance parameters are calculated on the basis of equations. These equations are the core of the methodology for the loss analysis.

Definition of pump losses

CURRENT

overall losses: $P^{P}_{loss,t} = P_{in} - P_{out}$

hydromechanical losses: $P^{P}_{loss,hm} = T\,\omega - T_{ideal}\,\omega$

volumetric losses: $P^{P}_{loss,v} = p_2\left(Q_{ideal} - Q_2\right) - p_1\left(Q_{ideal} - Q_1\right)$

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Energy losses are calculated as the difference between the power which is delivered to the system and the useful or intended power which is coming out of the system. But the overall losses don't tell us much about the origin of the losses. Therefore we need to split or segregate these losses.

In hydraulics, the overall losses are generally split into hydromechanical losses and volumetric losses.

The hydromechanical losses are calculated by comparing the measured mechanical power to the power based on a lossless, ideal cycle. In a similar way, the volumetric losses can be calculated by defining a kind of ideal flow rate.

These are the equations for pump losses. Similar equations can be made for motors.

Definition of pump losses

CURRENT

overall losses: $P^{P}_{loss,t} = T\,\omega - \left(p_2 Q_2 - p_1 Q_1\right)$

=

hydromechanical losses: $P^{P}_{loss,hm} = T\,\omega - \left(p_2 - p_1\right)\dfrac{V_g\,\omega}{2\pi}$

+

volumetric losses: $P^{P}_{loss,v} = p_2\left(\dfrac{V_g\,\omega}{2\pi} - Q_2\right) - p_1\left(\dfrac{V_g\,\omega}{2\pi} - Q_1\right)$

NEW

$P^{P}_{loss,t} = T\,\omega - \left(p_2 Q_2 a_2 - p_1 Q_1\right)$

=

$P^{P}_{loss,hm} = T\,\omega - \left(p_2 - p_1\right)\dfrac{V_g\,\omega}{2\pi} a_1$

+

$P^{P}_{loss,v} = p_2\left(\dfrac{V_g\,\omega}{2\pi} a_1 - Q_2 a_2\right) - p_1\left(\dfrac{V_g\,\omega}{2\pi} a_1 - Q_1\right)$

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The equations can be rewritten for parameters that can actually be measured. Also note that the sum of the individual losses equals the amount of overall losses.

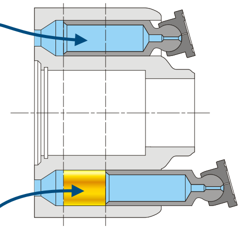
Our thermodynamic analysis has shown that the current loss equations can and should be improved. We believe they should be adapted in order to have a better understanding about the losses. We tried to stay close to the current conventions, and introduced two correction factors, a_1 and a_2, in order to get a better definition of the losses.

2 correction factors

minimum volume or dead volume
of a single displacement chamber

$$a_1 = 1 - \frac{\Delta p}{\bar{K}_s}\left(\frac{1}{2} + \frac{V_{\min}}{\Delta V}\right)$$

$$a_2 = 1 + \frac{p_2}{2\bar{K}_s}$$



$$\frac{\text{geometric displacement volume}}{\text{number of displacement volumes}}$$

Isentropic bulk modulus

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Both factors include the isentropic bulk modulus.

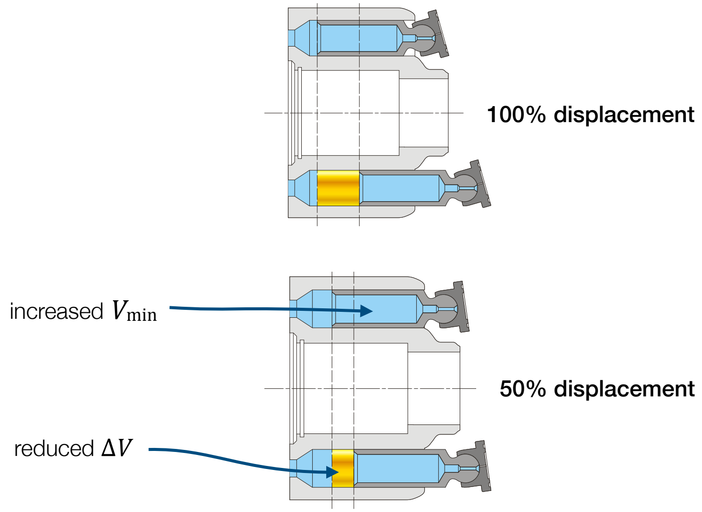
Furthermore, the factors include the geometrical displacement and the number of displacement chambers, in order to calculate the volumetric displacement for a single displacement chamber. These are, as such, not new parameters: they are also needed for the methodology described in ISO 4409.

Finally, and this is new, it must be known how large the dead volume is. This is the minimum volume of the displacement chamber.

2 correction factors

$$a_1 = 1 - \frac{\Delta p}{\bar{K}_s}\left(\frac{1}{2} + \frac{V_{\min}}{\Delta V}\right)$$

$$a_2 = 1 + \frac{p_2}{2\bar{K}_s}$$



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It should be noted that, in case of a variable displacement pump, the size of the dead volume V_{min} and the ΔV are both dependent on the displacement of the pump. When the displacement is reduced, the minimum displacement volume increases (at least in most pumps) and the ΔV reduces. As a consequence, the ratio $V_{min}/\Delta V$ increases when the displacement is reduced.

Definition of pump efficiencies

CURRENT

overall efficiency: $$\eta_t^P = \frac{p_2 Q_2 - p_1 Q_1}{T\,\omega}$$

hydromech. efficiency: $$\eta_{hm}^P = \frac{\left(p_2 - p_1\right) V_g}{2\pi\, T}$$

volumetric efficiency: $$\eta_v^P = \frac{Q_2}{V_g\, n}$$

NEW

$$\eta_t^P = \frac{p_2 Q_2 a_2 - p_1 Q_1}{T\,\omega}$$

$$\eta_{hm}^P = \frac{\left(p_2 - p_1\right) \frac{V_g}{2\pi}\omega}{T\,\omega}\, a_1$$

no definition

$\left(\eta_t \neq \eta_{hm} \cdot \eta_v\right)$

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It is not common to define the performance of pumps and motors in terms op power losses. In stead, the convention is to define efficiencies.

The equations on the left side show the current definitions for the overall efficiency, the hydromechanical efficiency and the volumetric efficiency. Only the first equation is a power ratio, which means it tells something about the energy efficiency. The second equation is a torque ratio, and the third a ratio of flow rates.

As a consequence of the new loss equations, the efficiency equations need to be changed as well. We believe it is possible to define the overall and the hydromechanical efficiency.

However, we have not found an equation for the volumetric efficiency, at least not as an energy performance parameter.

We have also come to the conclusion that, in general, it is incorrect to define the overall efficiency as being equal to the product of the hydromechanical and the volumetric efficiencies.

a_1 and a_2

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Now, what are these mysterious correction factors a_1 and a_2?

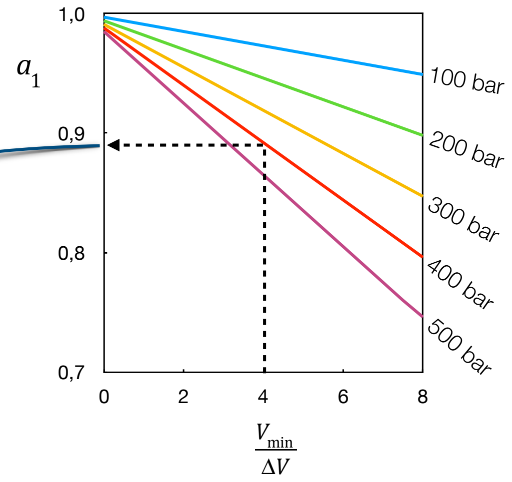
How significant are a_1 and a_2?

$$a_1 = 1 - \frac{\Delta p}{\bar{K}_s}\left(\frac{1}{2} + \frac{V_{\min}}{\Delta V}\right)$$

$$a_2 = 1 + \frac{p_2}{2\bar{K}_s} = 1 \ldots 1.02$$

example:

$$\eta^P_{hm} = \frac{(p_2 - p_1)V_g}{2\pi\, T}\, a_1 = 90\% \cdot 0.89 = 80\%$$



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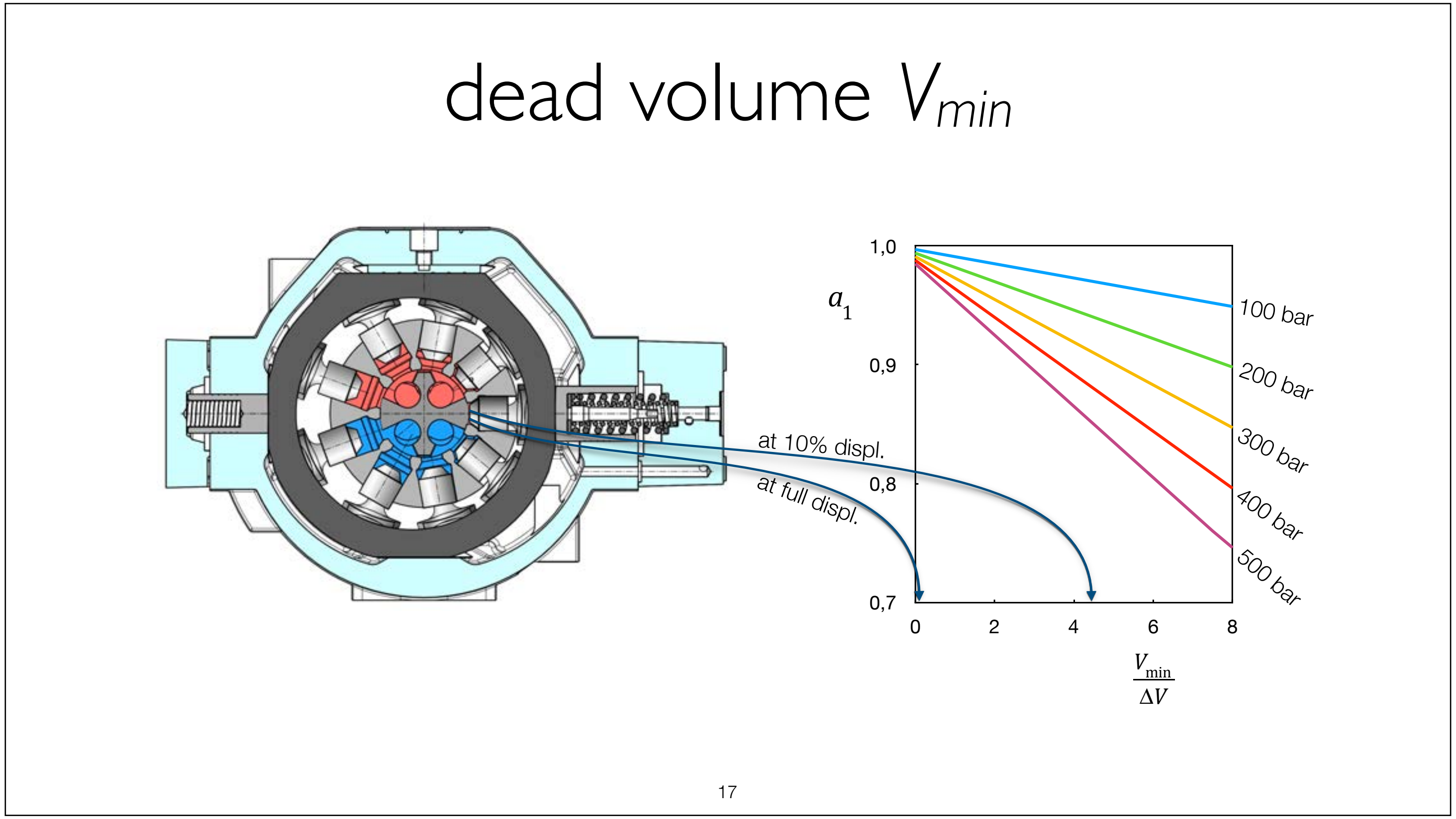
How significant are these factors?

The factor a_2 is dependent on the pressure level and varies between 1 and 1.02. We will see later if this is significant or not.

The other factor, a_1, has a much larger effect. In order to calculate this factor, the ratio between the dead volume and the *ΔV* has to be known.

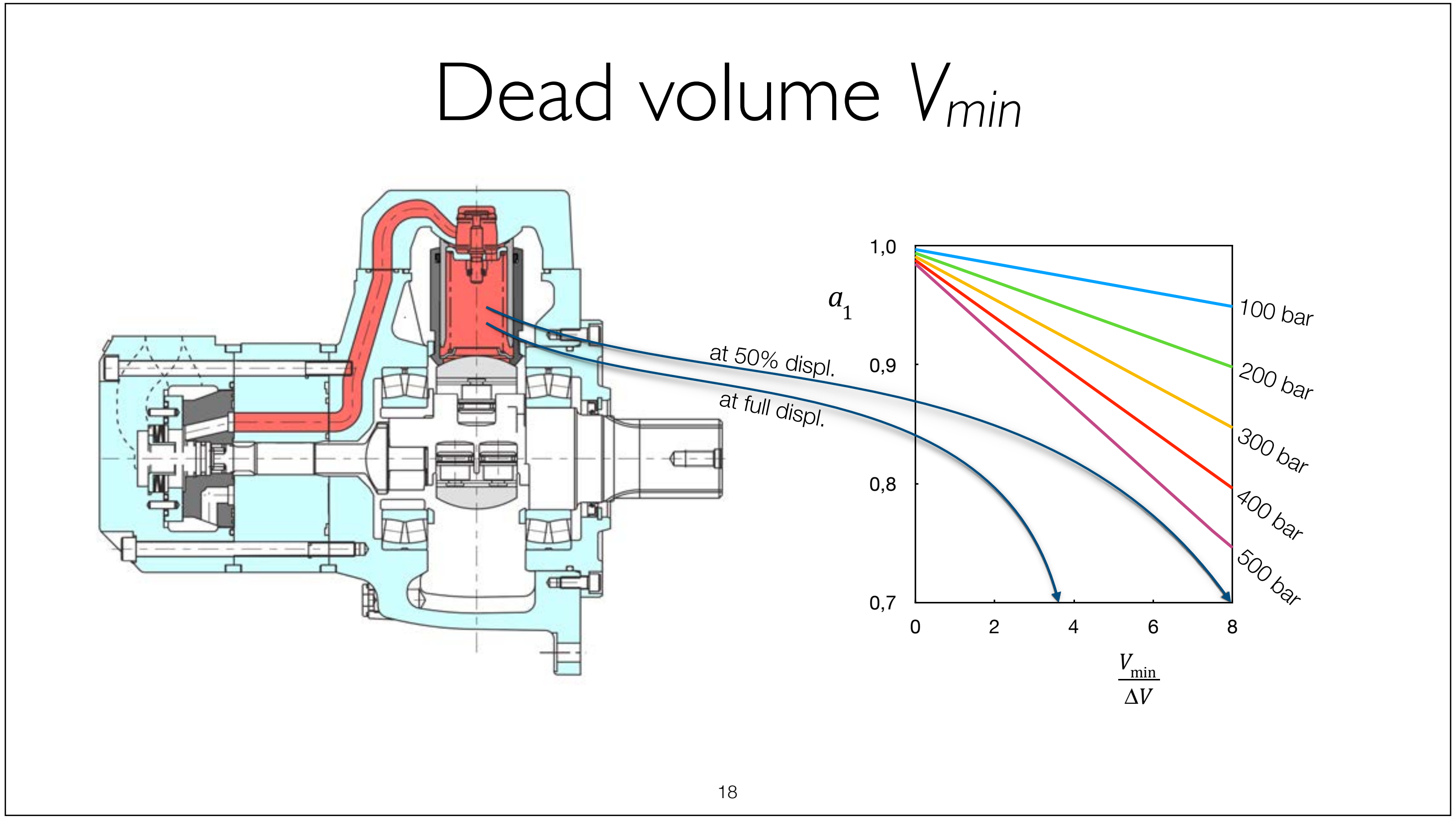
If this ratio is 4, and the pressure level would be 400 bar, then a_1 becomes 0,89. Let's assume that a pump would have a hydromechanical efficiency of 90% according to the conventional definitions, then this value needs to be reduced to 80% with the new definitions.



The amount of dead volume V_{min} is dependent on the design of the pump or motor. In this radial piston pump for instance, the dead volume is almost zero when the pump is operated at full displacement.

But this is variable displacement pump. A smaller displacement will not only reduce the value for ΔV, but it will also increase the dead volume.

As a result the ratio between dead volume V_{min} and ΔV is increased to a value larger than 4.



The situation becomes much more dramatic for this design, which has an extremely large dead volume.

Already at full displacement, the ratio of the dead volume V_{min} and ΔV is close to 4. This is also a variable displacement machine.

At a displacement of 50%, the ratio between dead volume and ΔV becomes close to 8, which has quite a large effect on the the factor a_1, and thus on our loss analysis.

Effect of the new equations

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We have calculated the effect of the correction factors on the measured efficiencies of two nearly identical slipper type machines: a pump and a motor.

Test of pump and motor

- 28 cc slipper type axial piston pump
- 28 cc slipper type axial piston motor
- $V_{min} / \Delta V = 0.78$
- INNAS Test Bench
- Shell Tellus 46 at 50°C inlet temperature

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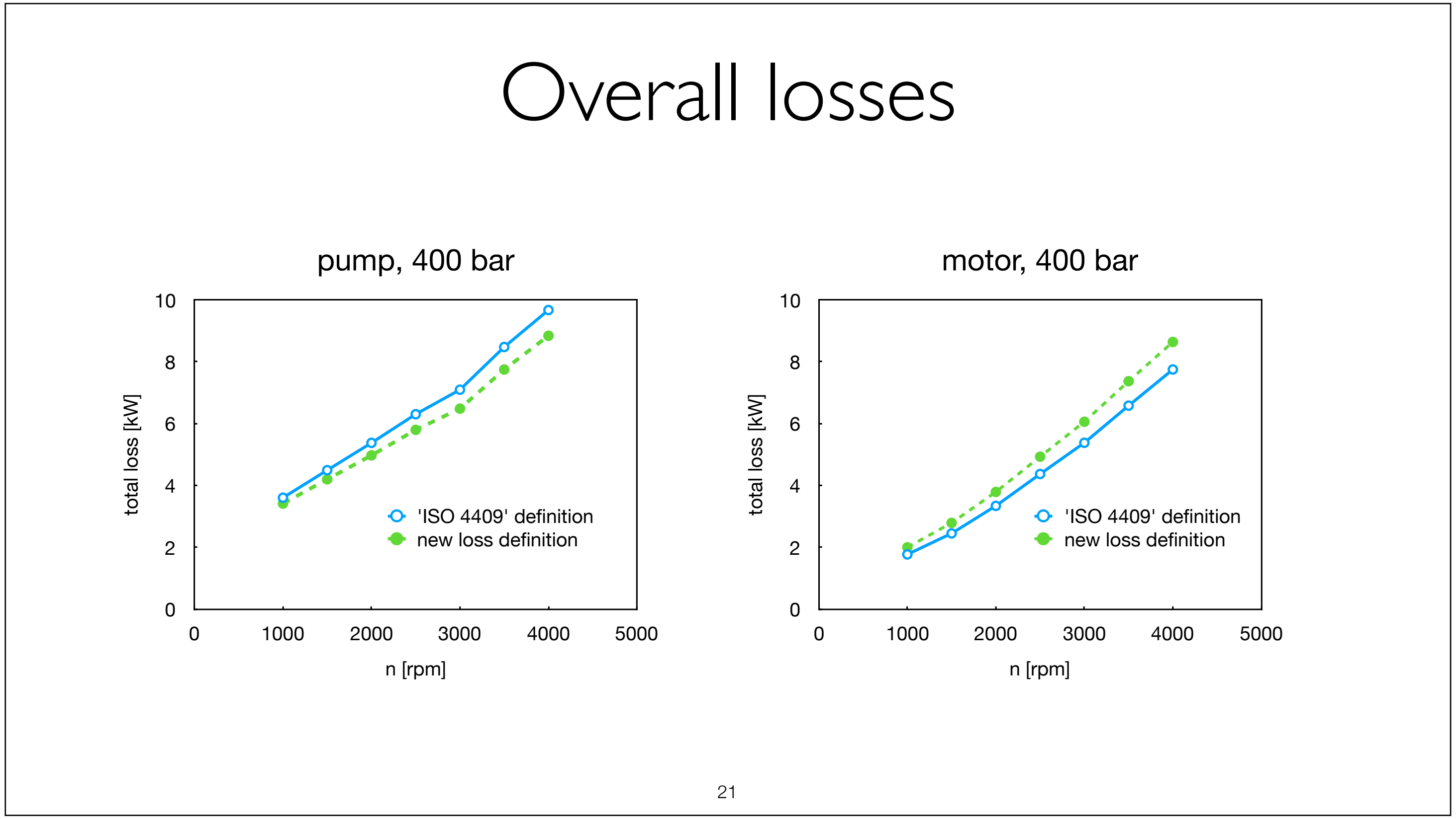
Both machines have a geometrical displacement of 28 cc.

The volumetric ratio $V_{min}/\Delta V$ equals 0.78 for these machines.

We tested both machines on our test bench, using Shell Tellus 46 oil at an inlet temperature of 50°C.

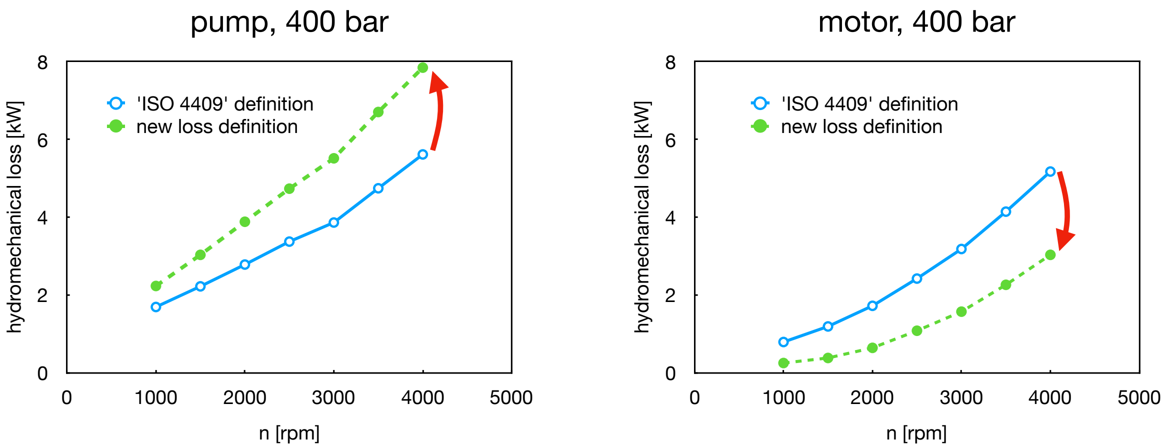


This diagram shows the overall losses of the pump, as calculated with the conventional definition and with the new definition.

It is important to realise that this diagram shows the losses, and not the efficiency. Whereas the effect of the new equation of the efficiency might be limited to 2%, on the losses the effect can be much larger. In this analysis the difference amounts up to 14%. From our point of view this is not to be neglected.

The second diagram on the right shows the calculated losses for the motor. The new equations result in a smaller overall loss for pumps and a larger overall loss for motors.

Hydromechanical losses



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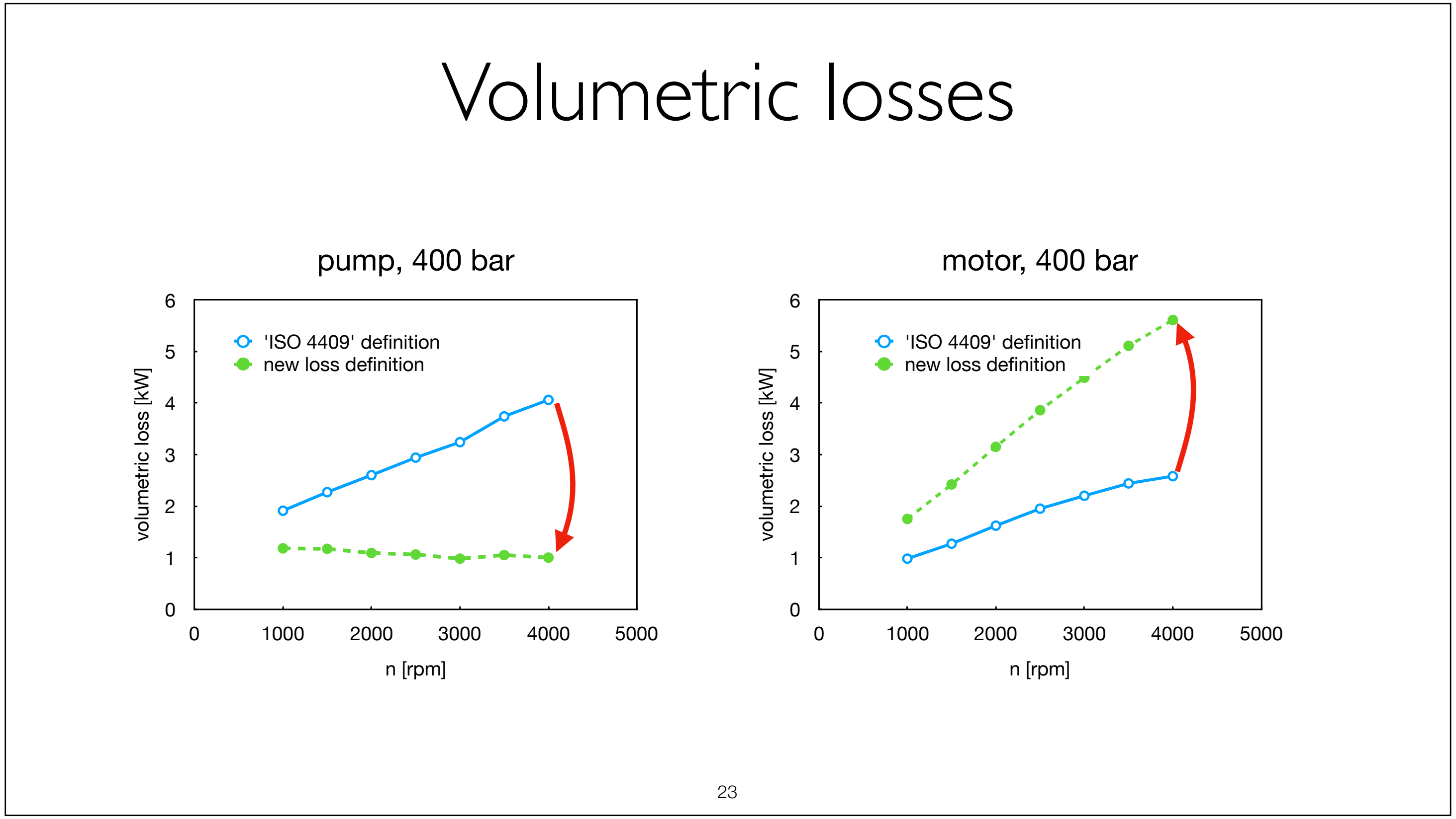
The effect of the new equations is much stronger on the calculated hydro-mechanical losses. For pumps, the losses are strongly increased, whereas in motors, the losses with the new equations are much smaller.



For the remaining volumetric losses, the differences are quite dramatic. Please remember that the ratio between the dead volume V_{min} and ΔV is rather small for this machine, and that the effects can be much larger for other machines.

Conclusions

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The conclusions from our analysis are quite clear:

Conclusions

- Include the effects of the bulk modulus and the dead volume in the analysis of pump and motor losses
- New definitions for power losses are derived
- New equations for the overall and the hydromechanical efficiency are derived
- We have not found an equation for the volumetric efficiency in terms of a power ratio
- Volumetric efficiency in terms of a ratio of flow rates is still possible

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We are convinced that it is important to include the effects of the bulk modulus and the dead volume.

We have defined new equations for losses, for both pumps and motors.

We have also been able to define new equations for the overall and the hydromechanical efficiency.

However, we have not been able to find a definition of the volumetric loss in terms of an energy or power ratio.

That having said, it is still possible to make a definition of a kind of a volumetric efficiency in terms of a ratio of flow rates.

Better separation of losses

- Standards for electrical motors and generators:
  - segregation in 6 individual losses
- Standards for hydraulic pumps and motors:
  - only 2 individual losses: volumetric and hydromechanical
- A more extensive loss analysis is needed
  - a first suggestion: commutation losses
- 'volumetric' and 'hydromechanical':
  Questionable semantics

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In the standards for electric machines, the overall losses are split into 6 individual losses, which allows a much better understanding of how these machines can be improved.

The current standard only distinguishes two individual loss sources: hydromechanical and volumetric.

We believe we need work on a better and more detailed segregation in the hydraulic standards as well.

A first suggestion would be to include commutation losses as an additional and separate loss source.

We also question whether the terms hydromechanical and volumetric are adequate, or maybe even misleading.

Recommendations

- Revise ISO 4409 (and other adjacent standards)
- Emphasis on loss analysis instead of efficiencies
- Introduction of more individual losses
- $\eta_t \neq \eta_{hm} \cdot \eta_v$
- Methodology is needed for determination of V_{min}

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Based on these conclusions, we recommend a revision of ISO 4409 and adjacent standards.

We also prefer to put an emphasis on power losses, in stead of using efficiencies.

We would also like to see and hope that in the future we will have more than just two individual losses.

Furthermore, we recommend not to use the classical equation anymore which defines the overall efficiency as the product of the hydromechanical and volumetric efficiency.

Finally, we need to agree on a methodology how to determine the minimum volume or dead volume of a displacement chamber.