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Evaluation Methodology of Rotary Flow Dividers Used as Pressure Intensifiers with Creation of a New Pressure Multiplying Efficiency

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Abstract: For most of the technical community, rotary flow dividers are known for synchronization of two or more hydraulic actuators. However, there is also a possibility to use them for pressure multiplication, flow regeneration, or speed control. For those applications, there is a need to describe the behavior of its quantities. This article reveals a new evaluation methodology for rotary flow dividers when they are unconventionally used as pressure multipliers and also reveals a new quantity-pressure multiplying efficiency. Then, there is an experiment provided between two rotary flow dividers with different designs, where there is a new evaluation methodology used. On the base of that, it is possible to compare and decide which divider is more likely to be used in multiplying circuits and more suitable for further investigation from the perspective of new designs. With this evaluation methodology, it is possible to compare much more than two different dividers. It is possible to run more tests and experiments with arbitrary dividers, and their new design changes to reach as efficient a pressure multiplication or flow regeneration as possible.

Keywords: rotary flow dividers; pressure multiplying efficiency; flow dividing inaccuracy; flow regeneration; pressure multiplication; experiment

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1. Introduction

Hydraulic circuits and their drives are building blocks in a wide range of machines and devices, for example, in forestry and construction machinery, mining machines, excavators, tractors, harvesters, and more. In most of them, the hydraulic circuit is driven by rotary gear pumps [1]. Following this utilization, gear pumps are the subject of many studies, which analyze their efficiencies related to Stribeck's values [2], volume efficiency [3], leakage [4], flow ripple [5], quiet run [6], cavitation [7], or wear life [8], or they describe them mathematically as numerical simulations [9,10] or description of turbulent flow within [11,12].

Gear motors are very similar devices to gear pumps. These are basically a gear pump running conversely. Gear pumps transform mechanical energy (torque from the drive shaft) into hydraulic energy, while gear motors use hydraulic energy to provide torque on the drive shaft.

Rotary flow dividers are close relatives of these two devices. Gear pumps and motors have drive shafts sticking out of them, which bring or take away torque, while rotary flow dividers do not have them. Their individual sections are basically gear motors connected together by one common shaft inside the device (thus sharing one common speed and also sharing one inlet). In many ways, it is possible to assign the same properties to rotary flow dividers as are defined for gear pumps and motors. They have, for example, the same gearings, housing dimensions, or gear bearings. Basically, one rotary gear motor represents one section of a rotary flow divider.

Rotary flow dividers are primarily used for linear motors synchronization [13,14], as can be seen in the case of lifting platforms or excavator buckets. Generally, they are used where there is a need for piston rods to extend at the same speed. In this kind of work mode, all divider sections are loaded with similar output pressure. Input pressure is equal to the average of all output pressures of the divider. This utilization is an alternative to synchronization, using, for example, a throttle valve with stabilization or tandem pump. The advantages include less heating than with a throttle valve and the ability to divide the flow closer to the actuators, which is not possible with a tandem gear pump. Rotary flow dividers could be also used for dividing the flow into the primary and secondary circuit, where different pressure is required.

When a rotary flow divider has only one section under pressure, it is possible to see an increasing difference between input and output pressure values. Output pressure is intensified. The question is: How efficient would it be to use a rotary flow divider as a pressure intensifier?

Specific multiplying ratios in particular cases are plainly described in articles [13–16], and also to be found in catalogues of rotary flow divider manufacturers [17–20]. Specific multiplying ratios will be described in detail in following chapters.

There is also literature explaining other competitive solutions, such as linear intensifiers [21], and their type of use. There are also other patents describing various types of pressure intensifiers [22,23] or pressure intensification assemblies [24–26]. The most common are linear intensifiers, some of which are even able to reach up to 800 bar. On the other hand, they demand high accuracy in manufacturing.

The knowledge and description of the divider's behavior (in work mode as pressure intensifier) are important for using a divider with the right properties in the circuit. This article describes a new evaluation methodology of rotary flow divider used as pressure intensifier, how to evaluate values from measurements of rotary flow dividers, and which quantities need to be monitored. In addition, new quantities have to be revealed and described.

There is an experimental measurement provided, which shows a comparison of two dividers with different designs as an example of the evaluation methodology's application. In this experiment, the importance of the new evaluation methodology could be seen. This methodology actually shows how efficient the rotary flow divider is in pressure multiplication. Therefore, based on results from this evaluation methodology, the following development of rotary flow divider designs used as pressure multipliers can begin to reach new and better results in pressure multiplication via rotary flow dividers.

2. Evaluation Methodology of Pressure Multiplication

Nowadays, there is general tendency of developers from various fields to create devices with as much energy savings as possible. This can be seen, for example, in transmission development [27] and also in hydraulic circuits. Energy savings can be found with the help of load-sensing systems [28] or, for example, with analysis of the right assembly for the most suitable drive's load position [29].

Pressure intensifiers used correctly in hydraulic circuits also help to save energy, especially in circuits where there are more drives driven by one source (pump) and there is a need for just one drive to work at a higher pressure than the others. Then, there is an advantage to use a pressure intensifier on the higher-pressure drive and let the rest of the system work on lower pressure.

For these pressure energy savings to be efficient, there is, of course, a need for the intensifying device (in this article, it is a pressure intensifier based on the concept of a rotary flow divider) to work as efficiently as possible.

2.1. Definition of Pressure Multiplying Efficiency

There is currently no traceable and precise description of a rotary flow divider's behavior when it is used as pressure intensifier. By being a divider, in principle an assembly of gear motors, an opportunity is offered to describe its behavior and work quality with efficiencies [3] used for descriptions of gear pumps and motors, especially volumetric efficiency and hydro-mechanic efficiency.

Volumetric efficiency η_v is simply a ratio of actual (Q_{actual}) and theoretical ($Q_{theoretical}$) output flow rate value (1), where theoretical flow rate is defined in Equation (2) as a product of geometrical volume V_g and speed n.

$$\eta_v = \frac{Q_{actual}}{Q_{theoretical}} \tag{1}$$

This efficiency defines how well a gear pump is able to transfer a volume of working fluid from its input to its output. Usually, some losses occur, such as leakage [4]; however, with the precise manufacturing of gear pumps or motors, the value of volumetric efficiency can reach 98%.

$$Q_{theoretical} = V_g \cdot n \tag{2}$$

Hydro-mechanic efficiency η_{hm} is a ratio of theoretical ($M_{theoretical}$) and actual (M_{actual}) torque on the drive shaft (3).

$$\eta_{hm} = \frac{M_{actual}}{M_{theoretical}} \tag{3}$$

It is possible to measure its actual value with dynamometers and compare it with calculated value from Equation (4) defined as product of geometrical volume V_g and output pressure p in case of gear pump or input pressure p in case of gear motor. The bigger the difference between actual and theoretical values is, the bigger friction losses inside a gear pump or motor are. They can be caused by too small clearances between components or low surface quality.

$$M_{theoretical} = \frac{V_g \cdot p}{20 \cdot \pi} \tag{4}$$

To describe a rotary flow divider with these efficiencies, there would be some conditions. Every divider section would be evaluated separately. That means dismantling the divider into separate sections. The hydro-mechanic efficiency of the divider could be measured that way, and the final value would be a product of values from every section. However, this would be a very complicated, inaccurate, and inefficient measurement. The assembly situation of the divider would lead to completing every section by adding new components, such as cover and flange, and specifically providing a new input for every section. Then, every section of the divider would be able to stand alone as a gear motor, and measurement could be implemented.

This way, it would be also possible to evaluate the volumetric efficiency. However, this would not be a good solution. Firstly, a rotary flow divider needs to be, in every case, evaluated by flow dividing inaccuracy. This quantity defines a divider's ability to precisely divide input flow into all of its outputs under pressure. Therefore, it describes the ability to transfer working fluid from the input to the output for every section separately, but with one big inseparable property. All sections interact with each other and relate to output pressure. Flow dividing inaccuracy is basically volumetric efficiency not defined as absolute numbers, but as a ratio with other sections.

It is possible to define the quality of pressure multiplication as the ratio of theoretical ($p_{theoretical}$) and actual (p_{actual}) input pressure (Equation (5)), where the calculations of ($p_{theoretical}$) will be described in following chapter. At first sight, it might seem like it is a hydro-mechanic efficiency that is defined with input pressure instead of torque (this is possible based on the fact that torque is a product of geometrical volume and pressure). However, another integral part of the multiplying process (besides mechanical losses) is the multiplying ratio. This is defined by each section volume or flow rate (where actual current value instead of theoretical must be calculated). Every section is a part of the multiplying ratio creation. Consequently, flow dividing inaccuracy also defines this ratio. It might be possible to say that flow dividing inaccuracy defines the stability and volatility of it. There are other phenomena as well, such as internal leakage or fluid transfer from input to output through axial clearances. In this case, flow dividing inaccuracy shows the output flow rate value, where some part of it does not interact with gearing and its torque. In addition, pressures incurred in piping on other than the multiplied output affects the final difference between input and multiplied output pressure. The derivation in the following chapters will show that all output pressures and volume ratios can be considered in the calculation. Thus, there would be no need to neglect anything.

$$\eta = \frac{p_{theoretical}}{p_{actual}} \tag{5}$$

For the forthcoming description and definition of the divider to be an analysis similar to those for gear pumps and motors in other studies [30,31], where FEA analysis or other calculations are used, there is a need to define the evaluation methodology, especially physical quantity, which would include all influences entering the process of pressure multiplication and thus precisely define the quality of the pressure multiplication via rotary flow divider. Let us call this the pressure multiplying efficiency.

Let us define the calculation for a two-section rotary flow divider with equal section volumes at first, and then define an n-section divider with section volumes that are not equal.

2.2. Two-Section Divider with Equal Section Volumes

As articles [13,32] state, when a two-section divider is connected to the circuit, there is one input and two outputs on the divider. A schema of the rotary flow divider is shown in Figure 1, which is, for these purposes, a simplified scheme from a patent [33], which pictures a rotary flow divider applied as a pressure intensifier. When output 1 (p_1) is plugged to the tank, there is no pressure on this branch. On output 2 (p_2), there is twice the pressure as there is on the input (p_0). If there is the same pressure (non-zero) on both outputs, there is the same value of the pressure on the inlet, so $p_1 = p_2 = p_0$. This thesis leads to the simple equation:

$$p_0 = \frac{p_1}{2} + \frac{p_2}{2} \tag{6}$$

When $p_1 = 0$, then:

$$p_0 = \frac{p_2}{2} \tag{7}$$

It is clear from Equation (7) that with the first section output plugged to the tank, there is half the value of pressure on the input as on the other output.

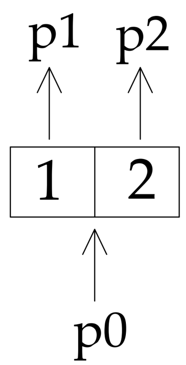

Figure 1. Two-section divider.

For the calculation of the real values, there is a need to add influences to the equations, such as mechanical losses or volume displacement inaccuracies. Let us implement pressure multiplying efficiency (η_{pm}), which represents all the real influences.

$$p_0 \cdot \eta_{pm} = \frac{p_1}{2} + \frac{p_2}{2} \tag{8}$$

After a mathematical adjustment, we have the following:

$$\eta_{pm} = \frac{p_1 + p_2}{2p_0} \tag{9}$$

The numerator of the Equation (9) ($p_1 + p_2$) is a sum of the output pressures. Half of its sum should be theoretically equal to the input pressure. Let us call this sum $\frac{p_1+p_2}{2} = p_{0t}$, where p_{0t} is the theoretical input pressure. Then, p_0 is understood as the value of the input pressure as really measured. This can be written as follows:

$$\eta_{pm} = \frac{p_{0t}}{p_0} \tag{10}$$

Pressure multiplying efficiency η_{pm} is defined as the ratio of the theoretical value of the inlet pressure and the measured (real) value. Output pressure is given by the load from the outer device (e.g., rotary or linear actuator). The rotary flow divider reacts to the output pressure load with the growth of the input pressure value. Therefore, the rotary flow divider does not actually multiply the input pressure to the output, but reduces the output pressure to the input by half.

2.3. N-Section Divider with Equal Section Volumes

In the previous paragraph, there was an input pressure equal to half of the sum of the output pressures (Equation (7). Pressure was divided by half, because there was a two-section flow divider with equal section volumes. Therefore, one section represents one half of the total volume value. If the premise is preserved that the n-section divider (Figure 2, where n represents number of sections) will be a divider with equal section volumes (demand for all sections), one section will represent exactly $1/n$ from the whole divider volume.

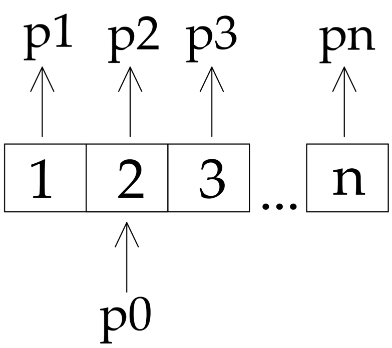

Figure 2. N-section divider.

Then we can assert the following equation:

$$p_0 = \frac{p_1}{n} + \frac{p_2}{n} + \ldots + \frac{p_n}{n} \tag{11}$$

In this case, there can be from 1 to $n-1$ sections without pressure plugged to the tank. If there are $n-1$ sections plugged to the tank, Equation (11) will be:

$$p_0 = \frac{p_1}{n} + \frac{0}{n} + \ldots + \frac{0}{n} \tag{12}$$

Input pressure is $1/n$ of the output pressure. If there is just one section plugged to the tank, and if the rest of the output pressures is equal ($p_1 = p_2 = \ldots = p_{n-1}$), Equation (11) will be:

$$p_0 = \frac{p_1}{n} \ldots + \frac{p_{n-1}}{n} + \frac{0}{n} = (n-1) \cdot \frac{p_1}{n} \tag{13}$$

Input pressure will be $n-1/n$ of the output pressure. For the efficiency, this also applies Equation (10).

If there is a need to define the Equation (13) for input and output pressures in general, let us say that n is the number of sections and i is the sequence of these sections, which are also the same volumes. Then, the input pressure is defined as:

$$p_0 = \frac{\sum_{i=1}^{n} p_i}{n} \tag{14}$$

For the efficiency, there is the same definition as in Equation (10). Therefore, if we bring it together with Equation (14), we can write:

$$\eta_{pm} = \frac{\frac{\sum_{i=1}^{n} p_i}{n}}{p_0} \tag{15}$$

2.4. N-Section Divider with Unequal Section Volumes

In previous chapters, we considered the same displacement for all sections. If there are unequal volumes of each section, there is no possibility to add the output pressures in the same ratio to generate the input pressure value, as in the case with the same displacement.

Ratio 1/2 from Equation (6) represents the basic ratio between one section's volume and the total volume. In general (Figure 3), this equation would be:

$$p_0 = \frac{V_1}{V_t} \cdot p_1 + \frac{V_2}{V_t} \cdot p_2 \tag{16}$$

where V_t represents total volume, and V_1 and V_2 represent arbitrary volumes of each section.

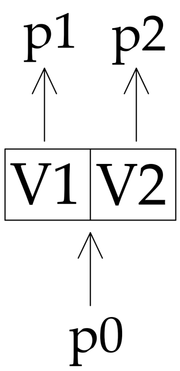

Figure 3. Two-section divider, different section volumes.

If we generalize Equation (16) for an n-section divider, we can obtain the following equation:

$$p_0 = \sum_{j=1}^{n} \frac{V_j}{\sum_{i=1}^{n} V_i} p_j \tag{17}$$

where V_i represents a specific section volume from all sections included in the divider, V_j represents a specific section from all the sections loaded with output pressure, and p_j represents pressure value belonging to the volume V_j. Therefore, this equation can count a value of the divider's input pressure for a divider with an arbitrary number of sections, without a condition for each section to be the same volume and under the same pressure load. This equation can be also explained from a power equation, where:

$$p_0 \cdot Q_0 = \sum_{i=1}^{n} p_n \cdot Q_n \tag{18}$$

$Q_{0...n}$ are flow rates belonging to the relevant outputs and input. If there is the same speed for every section taken into consideration and Equation (18) is edited, the result should be the same as Equation (17).

The final general statement of the pressure multiplying efficiency for an n-section divider with arbitrary section volumes and arbitrary output pressure loads is:

$$\eta_{pm} = \frac{\sum_{j=1}^{n} \frac{V_j}{\sum_{i=1}^{n} V_i} p_j}{p_0} \quad (19)$$

This Equation (19) is the result of adding Equation (17) to Equation (10).

3. Evaluation Methodology of Flow Dividing Inaccuracy

In general, flow dividing inaccuracy of rotary flow dividers is known as a difference of output flow values. In the case of a two-section divider, it is an absolute difference of both output values. For a divider with more than two sections, the inaccuracy is considered as an absolute difference of the maximum and minimum value of all output flow values. Therefore, every time it is a maximum possible difference between output flows.

For comparison of different dividers (different volumes), the difference between outputs is considered in ratio with maximum output value.

$$\eta_Q = \frac{Q_{max} - Qmin}{Qmax} [\%] \quad (20)$$

Rotary flow dividers are usually evaluated for their flow dividing inaccuracy based on a specified level of output pressure (e.g., 100 bar).

3.1. N-Section Divider with Equal Section Volumes

This general claim from Equation (20) is possible to implement for theoretical case of n-section rotary flow divider. So generalized standard evaluation methodology would be:

$$\Delta Q = |max < Q_1, Q_n > | - |min < Q_1, Q_n > | \quad (21)$$

Using values from Equation (27), there is an opportunity to compare two or more dividers with the same displacement. ΔQ values are absolute values, so there is a need for both dividers to be the same displacement for a comparison in flow inaccuracy. The better option, which allows us to compare any displacements of a rotary flow divider among each other, is to consider ΔQ in ratio with the maximum value of all the output flows (η_{Qi}). Therefore, using the standard methodology, which is known, it is possible to claim the following general statement:

$$\eta_{Qi} = \frac{\Delta Q}{|max < Q_1, Q_n > |} [\%] \quad (22)$$

Equation (22) defines flow dividing inaccuracy for those rotary flow dividers that are used, for example, for linear motors movement synchronization or other applications, where there is an emphasis on the equality of all output flow values. There could be another way to interpret flow dividing inaccuracy. This inaccuracy (η_{Qi2}) is a ratio between ΔQ and input flow Q_0. It interprets how big the amount of inaccuracy is (in percent) from the whole flow (meaning input flow Q_0).

$$\eta_{Qi2} = \frac{\Delta Q}{Q_0} [\%] \quad (23)$$

This value could be used for the assessment of applications where a rotary flow divider is used to divide flow rate into a primary and secondary circuit, where there is no dominance in the flow-dividing accuracy of the outputs, but there is a need to provide a minimum value of the flow rate in each of these circuits. In other words, it is a ratio, which provides easier dimensioning of a minimum pump flow (drawing all the flow into the system) that needs to go through the divider to provide the minimum flow needed in each circuit.

3.2. N-Section Divider with Unequal Section Volumes

There is a common methodology, which is described in the previous section. However, it needed to be extended for general use for an n-section rotary flow divider or converted into a different ratio used for primary and secondary circuits. When dividers with unequal sections are used, there is also a need to define a new flow-dividing evaluation methodology.

Let us assume that flow dividing inaccuracy for unequal dividers has a similar final definition as in Equation (22).

$$\eta_{Qi} = \frac{\Delta Q}{Q_{imax}} [\%] \tag{24}$$

The first thing that needs to be defined is Q_{it}. It is theoretical flow rate belonging to the specific section i, where i is from 1 to n. Q_{it} is defined as:

$$Q_{it} = \frac{Q_0}{\frac{V_{total}}{V_i}} \tag{25}$$

where Q_0 is input flow rate, V_{total} is the sum of all section volumes, and V_i is the volume of the investigated section (producing flow rate Q_{it}).

The next thing that needs to be defined is Δ_i. It is the difference between the theoretical and real (measured) value.

$$\Delta_i = \frac{Q_{it}}{Q_i} \tag{26}$$

In this case, Δ_i works as a tool for choosing the maximum and minimum flow rate difference from theoretical values, when all sections are compared. At this point, it is possible to define ΔQ as:

$$\Delta_Q = \Delta_{imax} + \frac{\Delta_{imin}}{m} \tag{27}$$

When a section with maximum flow rate difference and minimum difference is chosen, both values need to be compared on the same level. When a section with Δ_{imin} has a bigger geometrical volume than a section with Δ_{imax}, Δ_{imin} needs to be corrected with ratio m, which is defined as:

$$m = \frac{V_{imin}}{V_{imax}} \tag{28}$$

Here, V_{imin} and V_{imax} belong to the sections which are represented in (27) as Δ_{imax} and Δ_{imin}.

The final general equation after adjustments is:

$$\eta_{Qi} = \frac{\Delta Q}{Q_{imax}} = \frac{\frac{Q_{imin}}{m} - Q_{imax}}{Q_{imax}} [\%] \tag{29}$$

Equation (29) defines flow dividing inaccuracy in case of n-section rotary flow dividers with unequal section volumes, where it is not possible to use the standard evaluation method, which compares only sections with the same volumes.

4. Experimental Comparison of Rotary Flow Dividers

As an example to demonstrate utilization of the evaluation methodology, two of the most common types of rotary flow divider were chosen. These types are the most commonly used in applications and are easy to buy. The design of the first type is assembled without thrust blocks (NTB divider), while the second one includes them (TB divider), as shown in Figure 4a.

The TB divider's gears are assembled in thrust blocks and put together into a body that is closed with a cover. The NTB divider (Figure 4b) is assembled without thrust blocks, so the only difference is that the gears can be put together into the body directly. The body has blind holes ready for gears to be assembled.

Thrust blocks have a pressure-compensation function, so they are pushed against the gear faces. The result of using trust blocks is better flow-dividing accuracy, but there is an increase in friction losses. The rate of the influence of this phenomenon depends on the specific design of the divider. Therefore, the expectation is that the divider containing thrust block will have higher accuracy in flow-dividing, but due to bigger friction losses affecting pressure multiplying efficiency, lower values of this efficiency are expected.

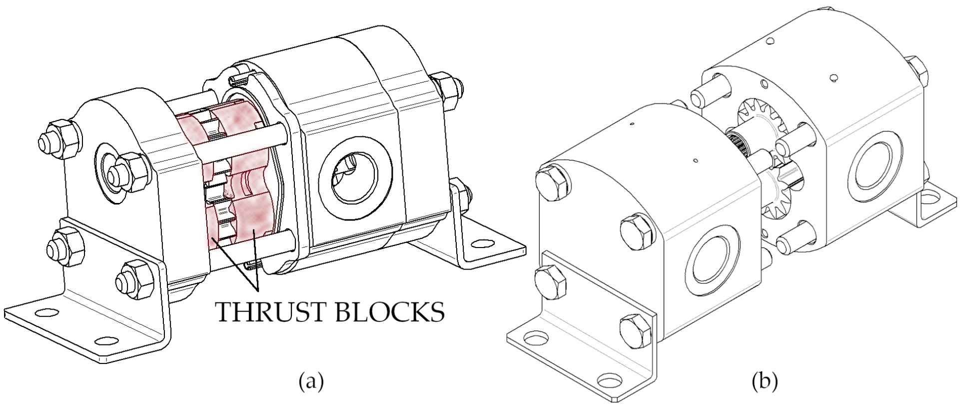

Figure 4. TB divider (**a**) and NTB divider (**b**).

Let us compare these two types of rotary flow divider using the new evaluation methodology described earlier in this article. For comparison, a pair of two-section rotary flow dividers were chosen. One includes thrust blocks and the second one does not. Both have the same gear parameters. Both have the same displacement $V_g = 10\ \mathrm{cm}^3$ per each section. This displacement was chosen as approximately middle displacement from the most common volumes, which are usually used.

Dividers were installed into a measuring circuit, as can be seen in Figure 5. Realization of the experiment and the circuit was performed in Jihostroj Velesin a.s., and measured dividers were connected to the stationary measuring stand.

The input flow is provided by assembly of the speed-adjustable motor and rotary gear pump of $V_g = 17\ \mathrm{cm}^3$. As with every hydraulic circuit, the safety valve is connected right on the pump output and was set on a release pressure of 270 bar. For monitoring the divider's input parameters, a manometer and flowmeter are assembled on the divider's input. There are also manometers and flowmeters on both outputs assembled for all output parameters to be monitored. The manometer on the left output (Figure 5) measures pressure p_1. This is the pressure that is multiplied to the final hydraulic device. In this circuit, the outer load is simulated with a throttle valve, which creates a pressure increase on the left output of the divider. The temperature of the working fluid (VG 46) was stable between 48–50 °C.

The manometer on the right output measures pressure p_2, which theoretically should be a zero value. However, there is passive resistance as friction in the pipes. Therefore, according to the Equation (19), there is no need to neglect small values of pressure (0–8 bar) based on passive resistance, and this is taken into account in pressure multiplication efficiency calculations for as precise results as possible.

There are also flowmeters assembled on both outputs, so there is a possibility to evaluate both flow dividing inaccuracy and pressure multiplying efficiency in one test drive. All three manometers used are the same type from Huba control with a declared resolution of 0.1% and range up to 400 bar. The flowmeter assembled on the input is set to 250 L/min, and two flowmeters are set to 160 L/min. All three of them are from Kracht company, with declared accuracy of ±0.3%.

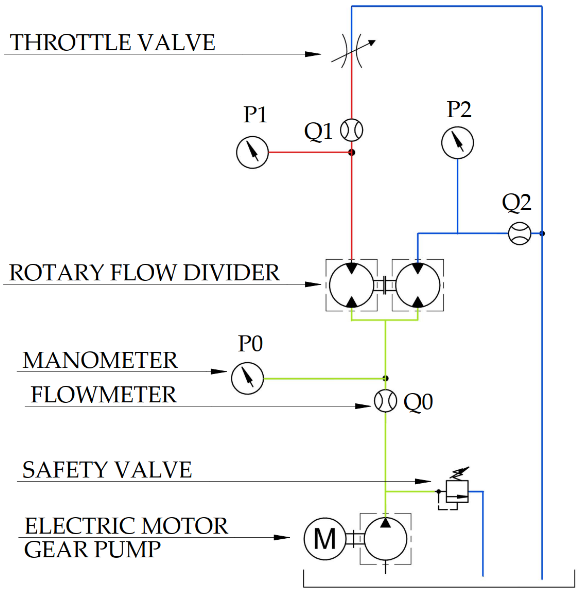

Figure 5. Hydraulic schema of measuring assembly.

4.1. Run of the Experiment

During the experiment, two dividers (NTB divider and TB divider) were gradually connected to the hydraulic circuit. Input and output pressures and flow rates were measured during four speed modes from 1000 min^{-1}, then 1500 min^{-1}, and 2000 min^{-1} to 3000 min^{-1} . To secure a precise speed mode of the divider, the flow rate of the gear pump was set up. During each speed mode, a throttle valve was in use to simulate an outer load affecting the divider, as can be seen in Figure 5. Pressure (secured from the throttle valve) was increased from 50 bar to 250 bar by 50 bar steps.

For the TB divider, there is a possibility to reach 300 bar according to technical sheet, without any further design changes. Therefore, (just for the illustration of the TB divider's behavior beyond the limit of 250 bar) its data were measured until 300 bar (maximum output pressure). For the evaluation between both dividers, a scale from 50 bar to 250 bar was considered.

All measured data were written down manually on a prepared data sheet.

4.2. Results of Measured Data from the Experiment

Measured data were evaluated in two stages. Firstly, the new evaluation methodology of pressure multiplication (described in previous chapters) was used. All the data of pressure values were counted, and courses of pressure multiplying efficiency in each speed mode are shown in Figure 6.

Efficiency η_{pm} for a TB divider is illustrated with blue splines. Efficiency for an NTB divider is shown as orange splines. There are four blue splines, which belong to one measured TB divider. Each of these splines are distinguished with a specific element belonging to a specific speed mode. Four orange splines belong to one measured NTB divider and are also distinguished by the speed mode. The same color of the four splines in the graph help visually illustrate the area in which the pressure multiplying efficiency is.

Until 200 bar, both efficiency splines can almost be seen as parallel, except the divider with thrust block spline for 3000 min^{-1}. This specific spline deviates from the area of the rest of the values from the very beginning. Above 200 bar, values of both dividers start to be different.

The TB divider curves have tendencies to approach one common value and descend from maximum values, which are around 88%. It could be also seen that pressure multiplying efficiency decreases with higher speed. In the first speed mode (1000 min^{-1}), the TB divider reaches the maximum value, but, as the graph shows, it is not possible to reach more than 200 bar output pressure, because the nominal speed of this divider is much higher than 1000 min^{-1}.

The NTB divider curves tend towards a common value but remain in a state of slow increase. The maximum value of pressure multiplying efficiency is over 90%, and it is reached in the speed mode of 1500 min^{-1}.

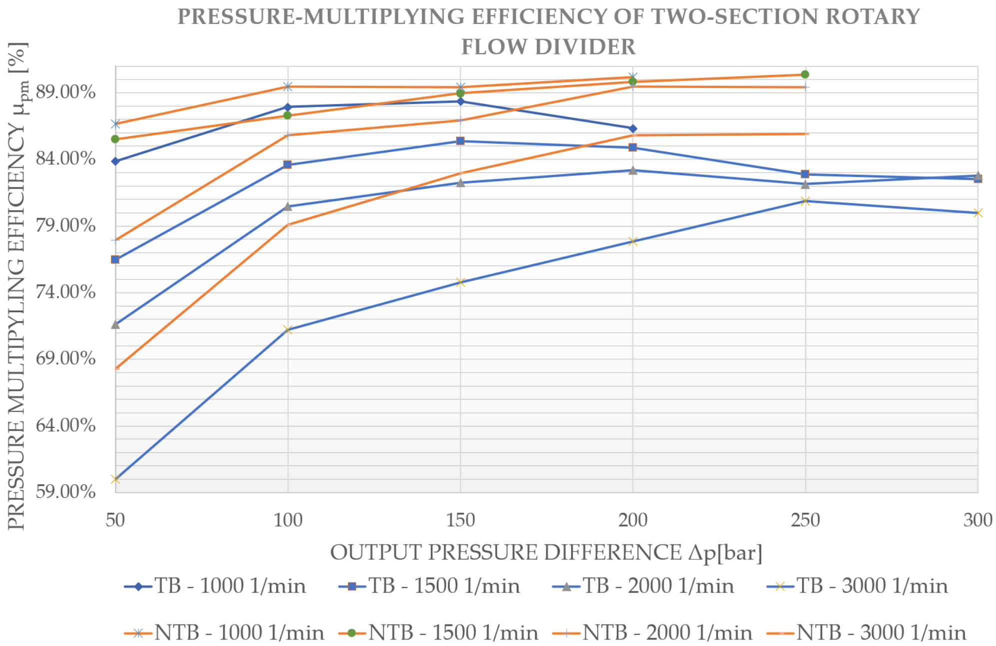

Figure 6. Pressure multiplying efficiency.

Both dividers completed the task of reaching 250 bar pressure output difference; however, some types of dividers are not able to reach 200 bar pressure output difference because of their design or manufacturing inaccuracy (which generally affects the smooth run of the divider).

As an addition to the evaluation of pressure multiplying efficiency, it is also helpful to evaluate the flow rate inaccuracy of both dividers. The divider could have very reasonable results in pressure multiplication but be affected by great losses in flow rate in multiplying the output. Then, it depends on preferences between higher speed (higher flow rate) and greater pressure-multiplying efficiency.

In the graph (Figure 7), flow dividing inaccuracy splines of the TB divider and NTB divider can be seen. Curves respond to the same speed modes as in Figure 6. All the data of pressure and flow rate values were measured at the same time. The y-axis represents flow dividing inaccuracy according to the first type of calculations (Equation (22)). The lower the values are, the better accuracy is.

According to Figure 7, the TB divider has higher accuracy in flow-dividing. All the curves increase with the load (pressure). The TB divider remains approximately steady until 200 bar, and then the values increase quickly. The NTB divider has increasing values from the beginning (approximately linear).

It is possible to say that in this comparison, with the help of the evaluation methodology of pressure multiplying efficiency, the NTB divider could be the more convenient choice for pressure multiplication, as can be seen in Figure 6, where values of η_{pm} are higher in every speed mode. It also starts on better efficiency values from the beginning of pressure loading. However, if the NTB divider were to be used in low-speed mode, flow dividing inaccuracy would be much more noticeable. In that case, it would be better to use the TB divider. On the other hand, if the aim was to reach 250 bar at a speed of 3000 L/min, the NTB divider could be a better choice, especially in applications where a lower flow rate during high pressure is sometimes required, for example in the case of a hydraulic press. If the divider should be a universal intensifier for all speed modes and pressure loads, the better choice would be the TB-divider, which has more stable behavior through the whole measurement, in exchange for poorer multiplication quality in some cases of operating parameters.

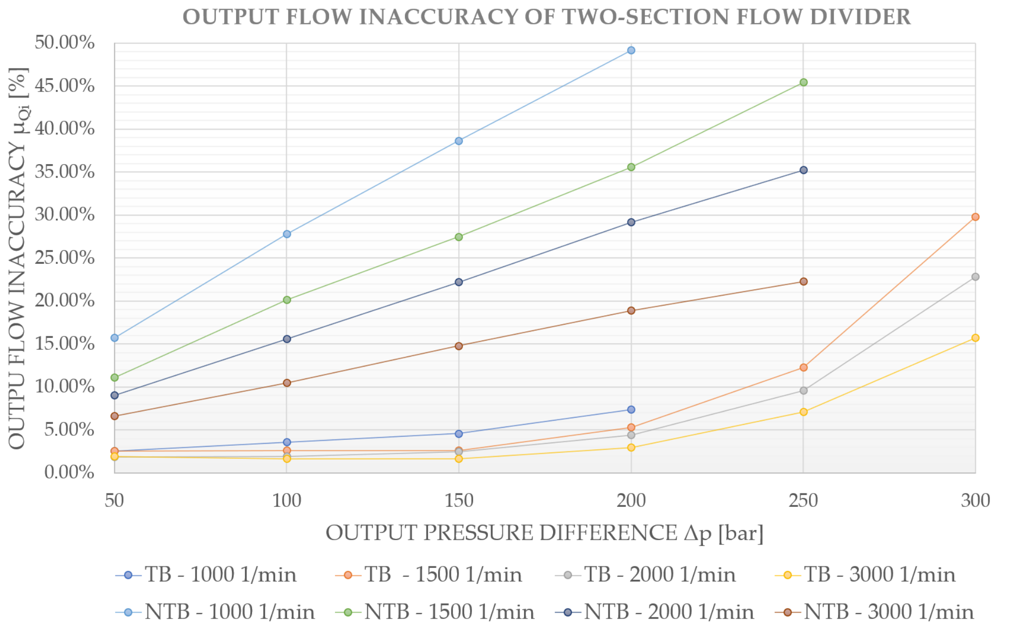

Figure 7. Flow dividing inaccuracy.

It is possible to state that the TB divider is better to use in applications with precise flow dividing, especially at speeds between 2000 and 3000 min^{-1}. Dividing inaccuracy stays between 1.63% and 9.6%. For the NTB divider, it starts at 6.65%, and at a 250 bar load, there is a 45 % value of the dividing inaccuracy.

With the knowledge of data from this evaluation, it is possible to precisely describe the behavior of rotary flow divider as a pressure-intensifier, and based on that, choose the best option for application as pressure intensifier. In addition, there is a possiblity to determine the best operating conditions for the divider to work as efficiently as possible in a hydraulic circuit.

To verify the repeatability of the measurement, the same types of dividers with the same parameters were assembled (one TB divider and one NTB divider) and measured under the same conditions on the same measuring circuit. Thus, the second measurement was done. The results tend to be very similiar and satisfactory, with 1.1% average difference of pressure multiplying efficiency values in the case of the TB divider, and 1.15% in the case of the NTB divider, proving the repeatability of the measurement. The NTB divider's flow dividing inaccuracy shows a difference of nearly 2.1% in relation to the first measurement, and for the TB divider's inaccuracy, it is nearly 0.7%. Since this experimental comparison is a demonstration of a new evaluation methodology utilization, the measured values from the second measurement were not included in the graphs, to make it easier to see important comparisons. The second measured values are used for verification of the truthfulness of the data interpreted in this chapter. When more samples are measured, then it will be possible to define this course of pressure multiplying efficiency (interpreted in this article) as stable, and deflection from this course can be considered as a failing of the device.

5. Conclusions

Rotary flow dividers are known in applications as movement synchronizers due to flow dividing. In these cases, there is an emphasis on flow-dividing accuracy. However, there is a possibility to use them as pressure intensifiers.

To use rotary flow dividers in this non-standard application, there is a need to evaluate their behavior in the process. There is not a methodology defined that would help to evaluate measured data. Therefore, an evaluation methodology of rotary flow dividers used as pressure intensifiers with the creation of a new pressure multiplying efficiency was formed.

This methodology deals with pressure multiplying efficiency for all cases possible, starting at two-section dividers with equal section volumes and ending with the definition for an n-section divider with arbitrary volumes of all sections. It could be used for a circuit where the divider is under pressure on just one outlet without neglecting unwanted pressure in outlet pipes plugged to the tank, or there could be the situation of multiplying evaluation, where more outlets are under the pressure, so one outlet is multiplied and another one under pressure is used with a lower pressure load in the secondary circuit.

As an addition to this new evaluation methodology, there is a generalized definition of flow dividing inaccuracy applied for an n-section rotary flow divider with arbitrary section volumes.

In this article, there is also an experimental comparison of two rotary flow dividers as an example of the new methodology's utilization. They are of different designs, so they are measured and loaded in the mode of a pressure intensifier, and with the help of the evaluation methodology of rotary flow dividers as pressure intensifiers, the behavior of multiplying efficiency can be seen. Therefore, the evaluated data clearly define the effectiveness of each divider's specific design, and it is possible to predict which one could be a better possibility for usage in pressure-intensifying circuits.

This evaluation methodology defines specifically how efficient pressure multiplication is. In contrast, there is mechanical efficiency (which shows an influence of friction and other passive effects on effective run), but it does not specifically define and explain the pressure multiplication.

Thanks to this new evaluation methodology, there is a possibility to uniformly evaluate rotary flow dividers as pressure intensifiers. In addition, there will be a possibility for further work with evaluated data in the progression of new modified designs specifically for the purpose of pressure intensification.

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