PRESSURE INTENSIFIER BASED ON THE CONCEPT OF A ROTARY FLOW DIVIDER

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Pressure intensifiers are used in specific areas of a hydraulic circuits, where increased pressure is needed, while the rest of the circuit (up to the pump) run on lower level of a working pressure. That could lead to a cheaper design of the components, while just one high pressure branch is designed on high pressure. Using pressure intensifier could also mean energy cost reductions.

Rotary flow divider can be also used as a pressure intensifier. This area started to be developed in Jihostroj a.s. This paper describes specific tests, which has been running to precisely parameterize limits of use of a divider as an intensifier without design changes to follow with a development of a designs to maximize intensifier's parameters. Development also leads to compact solutions compatible with LS signals or with other hydraulic components to create compact assembly comparable to some areas of use of a piston pumps or inexpensive flow control drive. These development opportunities are also described in this paper.

KEYWORDS

Pressure intensifier, Rotary flow divider, Hydraulic circuit, Compact solution, Test results

1 INTRODUCTION

Rotary flow dividers are most common in applications where synchronization of drives is needed. Divider can divide flow rate into two or more sections, where output flow rates are theoretically equal without addiction on output pressures. It is possible to say, every section can be imagined as hydraulic gear motor and all of them are connected firmly by one common shaft and sharing one common input. The result is one synchronized speed on every section without exception and subsequently synchronized output flow rates.

Pressure intensifiers [Gill 2009], [Latos 1995], [Baatrup 2008], [White 1991], [Nomura 2003], [Power&Motion 2014] are used in specific areas of a hydraulic circuits, where increased pressure is needed, while the rest of the circuit (up to the pump) is designed on lower level of a working pressure. That could lead to cheaper design of the components as e.g. hoses or directional valves, while just one high pressure branch is designed on high pressure. Using pressure intensifier could also mean energy cost reductions.

Rotary flow divider can be also used as a pressure intensifier. For example, two-section divider with equal section volumes, where one output is under pressure load and other goes to the tank without resistance, provides almost halved value of an input pressure (depends on efficiency, friction losses and other parameters) than the value of a pressure on loaded output. This phenomenon is observable thanks to power equation, which demands that input power must be equal to sum of the output power. It is possible to say, in divider's mode of pressure intensification section under pressure is a working section and the rest of the sections, which are plugged to the tank, are forming specific multiplying ratio with their section volumes. Simply put, they are helping the first section to multiply input pressure.

To be able to analyze rotary flow divider as it can be seen in many gear pump researches [Michael 2012], [Borghi 2009], [Sedri 2019], [Cao 2015] there has to be clearly defined behavior of rotary flow divider as pressure intensifier. It is not possible to use standard evaluations of work quality as for gear pumps and motors. Therefore, new evaluation methodology with creation of new pressure multiplying efficiency η_{pm} [Hradecky 2022] was created. This efficiency directly describes quality of multiplication with rotary flow dividers.

There has been running specific tests to precisely parameterize limits of use of a divider as an intensifier without design changes to follow with a development of a designs to maximize intensifier's parameters in Jihostroj a.s. Development also leads to compact solutions compatible with LS signals or with other hydraulic components to create compact assembly comparable to some areas of a piston pumps or inexpensive flow control drive. The methodology for evaluation rotary flow dividers used in running test has been developed in cooperation with CTU in Prague. From this methodology there is a possibility to evaluate arbitrary divider with arbitrary parameters and deduce suitable statements for description of divider behavior.

Intensifier based on the concept of a rotary flow divider can be also used for flow regeneration [Morgan 2002]. Divider divides its input flow rate, where one output goes back to the input of an actuator and the second output goes to the tank [Power&Motion 2013]. Phenomenon of a pressure multiplication can be useful in case of friction losses on returning branch.

2 PRESSURE MULTIPLICATION

In article Flow divider circuits [Power&Motion 2009] there could be seen the principal of pressure multiplication via rotary flow dividers. Where output V1 with section volume V_1 is under pressure and others (in case of Fig. 1 it is just one output V2 with section volume V_2, but generally there can be more of them) go to the tank without resistance (Fig. 1). Input pressure which goes to the divider is described as p_0.

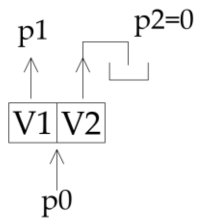

Figure 1. Schema of two-section divider - pressure multiplication

Figure 1 is also a simplified hydraulic scheme of patent describing pressure intensification via divider [Morgan 2008].

Generally multiplying ratio is a ratio between geometrical volumes of divider's sections. The ratio is defined as volume of section with multiplied pressure divided by total volume of the divider.

Pressure multiplication arises thanks to the ratio of volumes of each divider's section, it depends on ratio of section volumes. Theoretically, if there is a need to multiply output pressure p_1 three times, there could be three-section divider with the same volume of every section used, where two sections are plugged to the tank. Then there is a value of multiplying ratio 3 which intensifies input pressure to the output pressure three times. As an alternative, to preserve value of multiplying ratio 3, it is also possible to use asymmetrical two-section divider, where section plugged to the tank is twice bigger than section under multiplied pressure.

In recently described cases there is a description of theoretical cases without efficiency consideration. Generally, there is an accent to work as efficient and stable as possible in various areas of engineering [Lopot 2021] and thus in hydraulic systems [Lisowski 2021], [Stawinski 2021]. To describe a behaviour of divider and its pressure intensification properly and complexly describe the quality level of intensifier operation, there was new evaluation methodology invented and new pressure multiplying efficiency (2) derived and defined for general cases.

Simply put, efficiency η_{pm} is ratio of theoretical (p_{0t}) and measured (p_o) input pressure (1) – the pressure which goes into a divider as it could be seen in Figure 1. This efficiency defines clearly and complexly a quality of pressure multiplication from divider's input pressure to its multiplied output pressure [Hradecky 2022].

$$\eta_{pm} = \frac{p_{0t}}{p_0} \tag{1}$$

Pressure multiplying efficiency summarizes all effects that can possibly enter the theoretical calculations of the multiplication. The main part covers friction losses, there are also leaks and inaccuracy in flow-dividing (which alters theoretical volume ratio of divider sections), internal leakage or fluid transfer through axial clearances. This all has to be considered for accurate calculations.

Input pressure value p_0 could be measured from hydraulic schemes as for example in Figure 1. The question is a definition of theoretical value. There are section volumes and pressure and pressure losses on outputs plugged to the tank entering this calculation. It is also more complicated for n-section divider or a divider with unequal section volumes. In [Hradecky 2022] there was defined a calculation for n-section divider, with arbitrary section volumes and output pressures (2).

$$\eta_{pm} = \frac{\sum_{j=1}^{n} \frac{V_j}{\sum_{i=1}^{n} V_i} p_j}{p_0} \tag{2}$$

Denominator p_0 represents measured input pressure and numerator represents theoretical input pressure calculated as sum of output pressures with emphasis of section volumes ratio. Where n is number of sections, i is the sequence of these sections, V_j represents specific section from all the sections loaded with output pressure, V_i represents specific section volume from all sections included in divider, p_j represents pressure value belonging to the volume V_j.

In case of configuration in Figure 1, equation 2 would be simplified as equation 3.

$$\eta_{pm} = \frac{\frac{V_1}{V_1+V_2} \cdot p_1 + \frac{V_2}{V_1+V_2} \cdot p_2}{p_0} \tag{3}$$

V_1 and V_2 represents volumes of specific sections, p_1 and p_2 are output pressures and p_0 is input pressure.

There is no need to neglect pressure losses on outputs plugged to the tank, because equation 2 can calculate multiplication with arbitrary output pressures, which lead to more precise results. Of course, other output pressures don't have to be just losses in piping, but there could be also another low-pressure device added and equation 2 can be still applied.

3 TESTED SAMPLES

Experimental measurements were performed to obtain data of rotary flow divider's behaviour during loading as pressure intensifier. Its results can evaluate suitability of dividers (with various section volumes, speeds and structural designs) to transform into pressure intensifier.

Evaluation parameters are pressure multiplying efficiency, which is described within new evaluation methodology [Hradecky 2022], and flow dividing inaccuracy on various output pressure differences. So, it is possible to observe the behaviour of intensifier at different speeds during increasing pressure load.

Tested samples are several types of dividers from Jihostroj a.s. [Jihostroj 2021]. For clarity types of dividers are called A, B, C and D. Summary parameters can be seen in Tab. 1.

	PARAMETERS OF DIVIDER TYPES				
TYPE	V_g [cm^3]	n [1/min]	$p_{max\text{-}output}$ [bar]	T [°C]	DESIGN
A	2,1 - 10,0	1500 - 4000	300	-20 - 80	NTB
B	3 - 15	1000 - 4000	280	-20 - 80	TB
C	6 - 31	800 - 3800	280	-20 - 80	TB
D	10 - 25	1700 - 3500	300	-20 - 80	NTB

Table 1. Parameters of divider types

Geometrical volume V_g belongs to each section separately. Maximum output pressure is shown as output pressure, which guarantee flawless run, in case of standard usage of the divider.

Design of rotary flow divider can be assembled with thrust blocks (TB-divider in Fig. 2). These components dispose with pressure-compensated function, so they are pushed against the gear faces. The result is better accuracy in flow dividing and higher volume efficiency. On the other hand, simultaneously increase of friction losses occur.

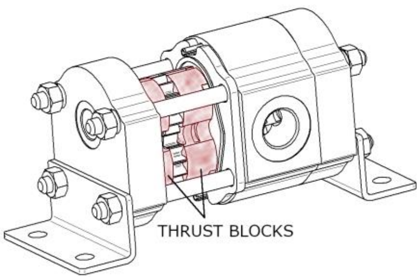

Figure 2. TB-divider [Hradecky 2022]

There can be divider without thrust blocks provided (NTB-divider). They can be an expectation of lower value of friction losses, but higher flow dividing inaccuracy.

Type A is a NTB divider which belongs to the smallest (in comparison of volume). Type B is a TB divider considered in the middle in comparison of divider volumes. Type C and D are the biggest ones, when type C includes thrust blocks in its assembly and type D doesn't. Bodies of NTB dividers are made of cast iron and on the other hand TB divider's bodies are made of aluminum alloy.

There were two sizes chosen from every type which represents small and big volume of every type. There were also asymmetric and three section dividers measured. For measurement repeatability, every sample is manufactured twice and tested for objective results.

Dividers are installed into measuring stand and its hydraulic scheme can be seen in Figure 3.

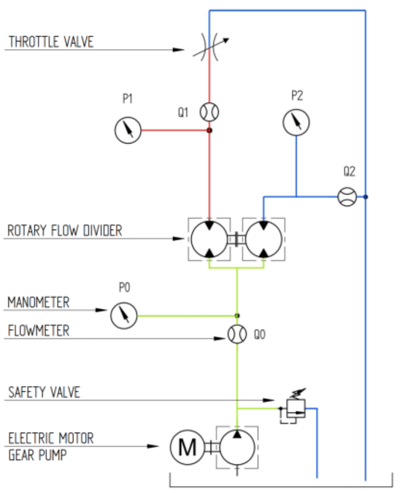

Figure 3. Hydraulic scheme of measuring stand [Hradecky 2022]

Input flow rate is secured by assembly of electromotor with adjustable speed and gear pump (V_g=17cm^3). As in every hydraulic circuit there is a safety valve set on 270 bar. To measure input pressure and flow rate, there is flowmeter and manometer installed between pump output and divider input. These sensors are also assembled on every output to monitor output values. Manometer on left output branch measures pressure p_1. It is a multiplied pressure which goes to the hydraulic appliance. Outer load is simulated with throttle valve.

Manometer on the right output branch shows pressure p_2, which should be theoretically zero. However due to losses in piping it is not true. Thanks to the equation 2 there is no need to neglect passive pressure p_2 and it is possible to calculate with this value to get more accurate results.

Measured values gained from flowmeters on both output branches secure the possibility to evaluate flow dividing inaccuracy from one experiment along with pressure multiplying efficiency. Temperature of a working fluid VG 46 ranges between 48°C and 50°C. All manometers from Huba control are ranged up to 400 bar with declared resolution of 0,1%. Flowmeter on the input is made to 250l/min and output ones are to 160 l/min. All of them are from Kracht company with declared accuracy of ±0,3%.

4 TEST RESULTS

Experimental measurements of all the samples mentioned in the previous chapter were tested to evaluate divider's suitability of various designs and volumes for transformation into pressure intensifier.

The main evaluation parameter for selection is pressure multiplying efficiency. As additional parameter for the whole picture of intensifier's behavior the flow dividing inaccuracy is considered. Thanks to these parameters it is possible to watch behavior during different speed modes and pressure load and output pressure difference which is considered as non-standard.

4.1 Marking of samples

All mentioned types of dividers has one common marking. As an example mark B-2x3 - 1500 1/min says with the first position, there is a divider type B, next position demands number of sections – two in this case. Third position stays for volume in cm^3 (in this case 3 cm^3). For this kind of marking, all section volumes are considered as equal. The last position defines speed mode in which the divider is currently operating.

In the folowing graphs on Figure 4, 5 there is one type of a divider in three speed modes. All three of them are pictured with one common color to picturize the borders of a working zone of the divider.

Asymmetric divider has slightly different marking. For expample B-10/5 is explanied as B-type divider with one section of V_g=10 cm^3 and second section with volume V_g=5 cm^3. There could be also the definition of a speed mode in the marking, however in Figure 6 there are all the speed modes averaged into one characteristic line to demonstrate total difference between specific samples.

4.2 Two-section TB dividers

Type B dividers with small volume value has problems to transfer bigger output pressure difference and it was not possible to reach value of 200 bar. In Figure 4 it is possible to see characteristics with black color. However flow dividing inaccuracy didn't reach the border of 5%.

Dramatically different results came with type B dividers with big volume values. There could be seen in Figure 4 with blue color the rising tendency with inclination for one common value above 85 %. There was also reached the aim of 250 bar without problems. The flow dividing inaccuracy rises with rising pressure load from 2 % to 12 %.

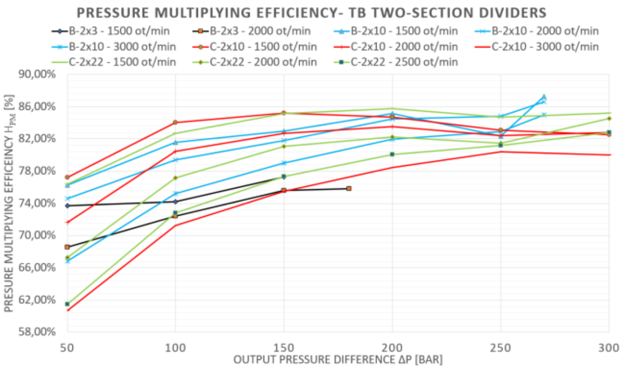

Figure 4. Pressure multiplying efficiency - two section TB divider

Type C divider with small volume value reaches 300 bar pressure difference without hesitation. Pressure multiplying efficiency reaches 88% within 150 bar pressure load. Under higher pressure there is also to be seen inclination to the one common value around 80% as in case of type B divider with higher volume value. Flow dividing inaccuracy stays under 4,5% until 200 bar output pressure. Then the value increases rapidly above 15% (at 300 bar). Type C divider characteristics are pictured with red color.

Type C divider with big volume value tend to have approximately similar behavior as Type C with small volume value, however pressure multiplying efficiency maximum is 2% higher, so this type reaches 90% maximum border. Efficiency curves also tend to gather to one common value of 84%. Flow dividing inaccuracy is also better by 0,5%, but after 250 bar load there is also tendency to fast increase. This divider is pictured with green color.

4.3 Two-section NTB dividers

Generally, for NTB dividers lower mechanical losses are expected so higher value of pressure multiplying efficiency is expected at every pressure load. On the other hand, there is a need to consider worse quality of flow dividing inaccuracy.

Type A divider with small volume value reaches expected pressure load of 200 bar against B divider with similar volume, which wasn't able to reach that boarder. Type A divider reaches maximum of efficiency 87%, it can be seen in Figure 5, where this divider is pictured with black color. Flow dividing inaccuracy begins on 8% value and increases to 65%, which is not an acceptable characteristic.

Type A divider with big volume value reaches expected pressure load on speed of 2000 1/min. Needless to say, lower speed is (in case of this divider's type) considered as lower than operating speed. Course of pressure multiplying efficiency cannot be considered, compared to other types, as stable. Its maximus is 84%. In comparison with A divider with small volume, there is an improvement to be seen in flow dividing inaccuracy. Values does not increase so quickly with increasing output pressure, but also reaching 30% at maximum value. In Figure 5 this divider is pictured with blue color.

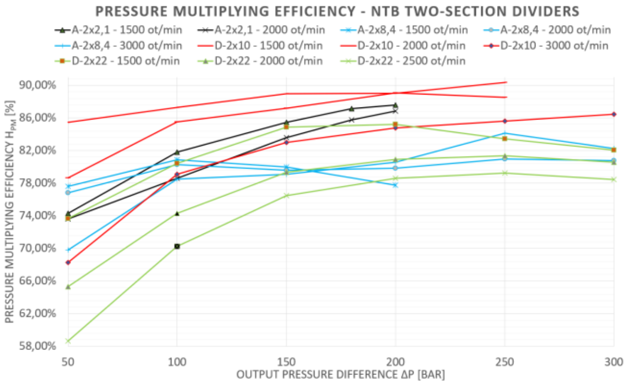

Figure 5. Pressure multiplying efficiency – two section NTB divider

Type D divider with small volume value transferred 300 bar pressure load without hesitation. Its pressure multiplying efficiency maximum is over 90% and its tendency increases. Flow dividing inaccuracy linearly increases from 7% to 45%. Divider is represented with red color.

Pressure multiplying efficiency behavior of type D divider with big volume value rather reminds characteristics of TB divider type C, also reaches similar values. Maximum is nearly 86%. The whole characteristics incline to common 81%. Flow dividing inaccuracy is almost linear and goes from 6% to 35% with increasing output pressure.

4.4 Asymmetric dividers

There are two basic parameters for evaluation of pressure intensifiers based on concept of rotary flow dividers: pressure multiplying efficiency and multiplying ratio, which is composed of geometrical volumes of each section. Three-section divider can be plugged to multiply output pressure three times, when two sections are plugged to the tank and the third section is the one under the load (it is applied for cases when volumes of all sections are equal). As an alternative to three-section dividers there is a possibility to use asymmetric dividers (dividers with unequal volume of its sections). When two-section asymmetric divider with ratio of section volumes is 2:1 and bigger section is plugged to the tank, the same multiplying ratio occurs. Using asymmetric divider is also cheaper alternative, one section less than in case of three section divider is used. The result are savings of approximately one third of the cost of three section divider. The question is if the quality of asymmetric divider multiplication is comparable to other dividers. Let´s see in the following graph (Figure 6) and evaluate this quality with help of pressure multiplying efficiency.

As two-section asymmetric divider has one gearing less than three-section divider, so two friction surfaces (faces of gearing) are saved, the expectation is less friction losses and so higher value of pressure multiplying efficiency.

It is possible to see in Figure 6 (where all the speed modes are averaged into one characteristic line to demonstrate total difference between specific samples), the best results of pressure multiplying efficiency is attributed to three section divider B-3x10 (TB three divider representative). In average under load of 250 bar efficiency reaches 85% and with that exceed its alternative asymmetric divider B-10/5.

Generally, in case of type B dividers there are big differences between bigger and smaller section volumes. While smaller dividers have problems to reach bigger value of output pressure and reach acceptable values of pressure multiplying efficiency, dividers with bigger sections dispone with flawless transfer of high output pressures. In case of B-type asymmetric divider, the lower characteristic can be affected with the volume of smaller section which belongs to problematic volumes. Also, this asymmetric divider is not direct substitute for three section divider, because type B cannot provide the volume 20 cm³ of one section which should be a substitution for two 10 cm³ sections from three section divider. Therefore, it is possible to say, that the results of asymmetric divider is satisfactory, and in case of special manufacturing of divider with 20 cm³ section and 10 cm³ second section, the expectation would be for higher values of pressure multiplying efficiency than three section divider.

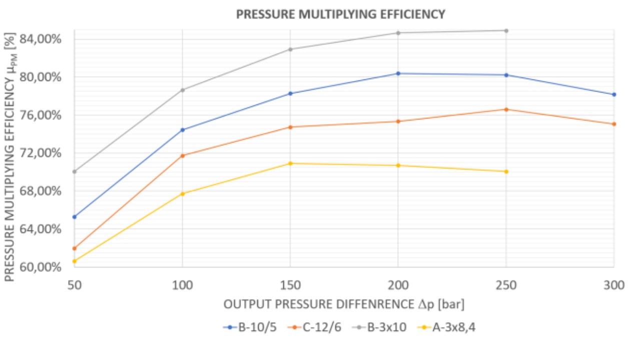

Figure 6. Pressure multiplying efficiency - asymmetric dividers

Type C divider has great results in both small and big section volumes. It is reasonable to assume, the results for asymmetric divider C-12/6 (Figure 6) will be higher than for B-10/5. But the opposite is true. Divider C has average maximum of pressure multiplying efficiency 77%.

As representative of NTB three section dividers there is A-3x8,4 divider introduced (Figure 6). This divider tend to be the one with the worst pressure multiplying efficiency in this comparison. In average its maximum reaches 71% at 150 bar.

For evaluation of flow dividing inaccuracy there was a need to expand the current methodology [Hradecky, 2022]. The most accurately dividing belongs to asymmetric divider B-10/5, which divides precisely and under 4% of flow dividing inaccuracy, the only exception is outer load of 300 bar, there is inaccuracy slightly above 5%.

Until 200 bar, the second best would be asymmetric divider C-12/6, which is practically the same with divider B-10/5. But after reaching 200 bar, flow dividing inaccuracy increases almost linearly to reach more than 40% of flow dividing inaccuracy.

Flow dividing inaccuracy of TB three section divider B-3x10 is located between 5% and 8%, but there is also a tendency to reach higher value at higher pressure load (15% at 250 bar).

As it is expected, NTB three section divider A-3x8,4 has linearly increasing flow dividing inaccuracy from the beginning, where the value starts on 8% and goes above 20% at 250 bar output pressure. This three-section divider was added into comparison mainly because of pressure multiplying efficiency reference.

4.5 Choice of leading type for pressure intensifier

For choosing a type stated for further investigation and development there is the main parameter pressure multiplying efficiency, especially its course at increasing output pressure and predictability of its behavior, which can help to define and predict stabilized work with dependance on other parameters.

Also, there is flow dividing inaccuracy involved. Its value increases with growing output pressure. However, in case of pressure intensifiers there is not so big accent on this parameter as it is in case of dividers used for flow synchronization where all the outputs have the same importance. Pressure intensifiers have one main output, where pressure and flow rate are controlled. Other output or outputs (which are plugged to the tank) are considered as the drain. Therefore, it is possible to state, that when noticeable inaccuracy in flow dividing occurs and influences the main output. This influence can be managed with an adjustment of section volume. On the other hand, adjustment cannot be really striking, there would be consequently changed the multiplying ratio too much. So, when type of divider is choosing to be used for further investigation, its flow dividing inaccuracy should not reach the boarder of roughly 35%. Then it is possible customize the development to comply with required output flow rate and multiplied pressure.

The best candidate to be design into compact pressure intensifier is divider type B. This type of a divider checks every parameter needed for two-section, three-section and even for asymmetric divider. It has satisfactory values of pressure multiplying efficiency and its predictable behavior, where its curves converge to one common value. Flow dividing inaccuracy is also very satisfactory in all cases. Overall type B dividers are really persuasive to become pressure intensifier.

4.6 Prove of consistence run on high pressure 400 bar

To become pressure intensifier and claim its output pressure values to be 400 bar, there is a need to prove this statement. Divider B-2x10 is chosen. The same hydraulic scheme of measuring stand as it is in Figure 3 was used. Temperature of a working fluid VG 46 ranges between 48°C and 50°C.

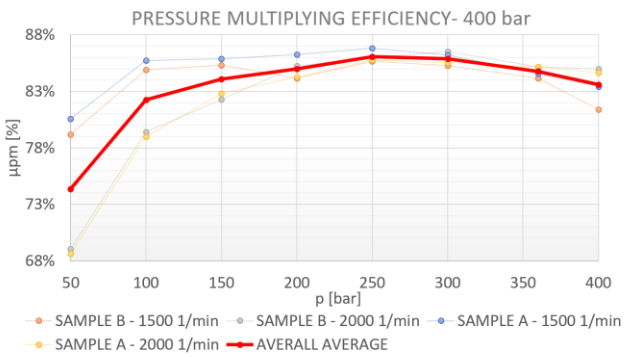

Figure 7. Two section TB divider – pressure load up to 400 bar

There were two samples manufactured to prove repeatability of this experimental measurement. Every sample was measured in two speed modes 1500 1/min and 2000 1/min. From four measurement (two samples at two speeds) the average behavior curve was made and in Figure 7 is pictured with thick red color.

Both samples proved corresponding behavior of pressure multiplying efficiency as the results from chapter 4.2 *Two-section TB dividers*. New results after 300 bar output pressure load showed consistency with the value of efficiency, where there is minor dicrease documented to final value of nearly 84% in average on 400 bar output pressure.

Flow dividing inaccuracy of both samples was very satisfactory. In average at 400 bar there was value under 11,5%. This value also has to be considered as value under the most burdensome parameters, so in case of output pressure less than 400 bar, the result will be always better than border value 11,5%.

There was also long-term measurement provided on both samples. The aim for both dividers was to stay stable on 400 bar output pressure, speed of 2000 1/min and match the values from previous measurement pictured in Figure 7.

All conditions have been met. So, it is possible to claim, that this type of a divider can be used as pressure intesifier to reach 400 bar output pressure.

5 UTILIZATION

General benefit of pressure intensifiers is a possibility to multiply pressure in hydraulic circuits where needed and also where the results are energy savings in overall evaluation of the whole circuit.

An example could be hydraulic multipurpose machine with three branches on lower pressure and one with higher, all driven by one pump. To avoid big energy losses on three branches, when pump would need to run on higher pressure, it is possible to install pressure intensifier on one branch with higher pressure. Then pump can run on lower pressure to support three lower pressure branches and also higher pressure branch, where the required pressure in intensified from lower pressure using pressure intensifier.

There are various designs of pressure intensifiers like linear intensifiers to multiply pressure even over 800 bar or accumulators to cover up pressure peaks. The advantages of pressure intensifier based on concept of rotary flow divider are compact dimensions, easy to dimension in relationship to input flow rate of final appliance, when linear intensifier is limited with maximum ejection parameter. But the main advantage of pressure intensifier based on concept of rotary flow divider is continuous run. It is able to multiply pressure to a required value and in parallel provide full needed flow rate for arbitrary amount of time. This feature opens the whole new areas of utilization.

5.1 New areas of utilization

Talking about pressure intensifier based on concept of rotary flow divider as an alternative to other intensifiers is one point of view. Using this kind of intensifier in connection with other hydraulic drives can lead to alternative solutions of the whole drives or even completely different hydraulic components.

The first utilization can be connection with regulated low-pressure vane pump in assembly as it is to be seen in Figure 8 as simplified scheme. Vane pump secure regulated flow rate, however does not provide high pressure. Therefore, there is an intensifier to secure sufficient output pressure. Thanks to continual intensifier's delivery, this assembly can secure flow regulation and also required output pressure and therefore be seen as a cheaper alternative to flow regulations via regulated speed of (electro) motor or regulated piston pump.

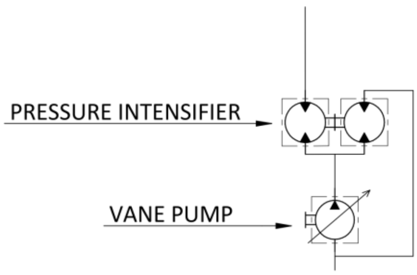

Figure 8. Regulated vane pump and pressure intensifier assembly

Rotary divider as intensifier plugged on the output of a pump (e.g. gear pump) can serve as instrument for covering pressure peaks in circuits. Utilization can be found in applications, where the same function would accumulator provide, but the hydraulic circuit has difficulties with recurring pressurizing of an accumulator because of accumulator's use and work character of hydraulic circuit. Pressure intensifier doesn't have to be plugged directly on pump output, but can be places on typed problematic area of the circuit.

According to results from chapter 4.6, assembly of gear pump and rotary pressure intensifier can provide 400 bar output pressure. Therefore, it is possible to consider this assembly as an alternative to piston pumps in applications, where piston pump is not used on its full pressure capacity, but it is also not possible to use gear pump, which cannot reach 400 bar by it-self. Advantage could be also lower demand on working fluid quality, because piston pumps require higher clearance quality of working fluid than gear pumps and rotary flow dividers. So also costs for maintenance of fluid quality could decrease.

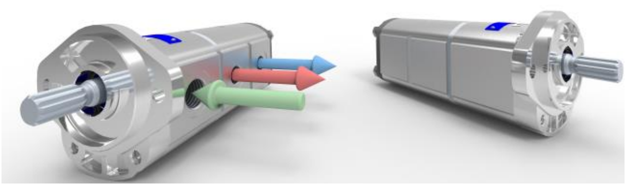

Figure 9. Gear pump and pressure intensifier assembly

In Figure 9 there is to be seen lay-out of compact solution of gear pump and pressure intensifier assembly, which looks like a tandem gear pump on the first sight. The first section works as a gear pump with suction area pictured with green arrow. The rest of this assembly is a two-section divider (pressure intensifier), where the multiplied output is outlined with red arrow and the last output with a blue arrow is plugged to the tank without pressure resistance. This solution can have various connecting dimensions of a flange or drive shaft, so it is possible to install it on the rest of a machine without any obstacles.

There is a tendency to regenerate flow rate in hydraulic circuits where linear hydraulic motor is present.

Not so unique problem of hydraulic circuit with flow regeneration using flow regeneration valves is friction losses in regeneration branch. According to this the wrong run of the system may occurs. Using rotary pressure intensifier as in simplified hydraulic scheme in Figure 10, this problem can be solved [Morgan 2002], [Power&Motion 2013].

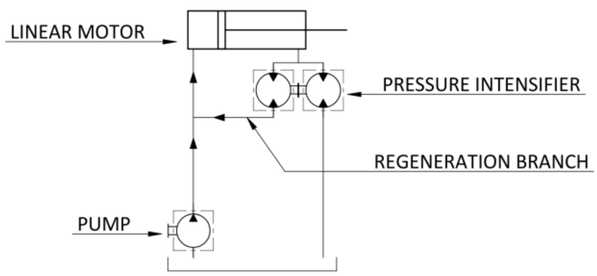

Figure 10. Flow regeneration using rotary pressure intensifier

In case of piston ejection, output flow rate from linear motor is divided via two-section rotary flow divider. One half of the delivery goes back to input of linear motor and helps the pump with delivery. The other half goes right to the tank. In this scenario rotary flow divider works also as pressure intensifier, where left section is the multiplied one and is able to overcome friction losses in regenerating branch. Another advantage is distribution of one part of the flow right into the tank, where cooling of working fluid occurs. It could prevent problems with overheating of the whole circuit.

There are also various possibilities for customization. Volumes of both sections can be in arbitrary ratio and therefore there is an opportunity to define how much flow rate would be regenerating and how much would be determined for cooling within the tank. Ratio also defines the amount of possible multiplication, so in case where there is another appliance plugged on regeneration branch, flow regeneration of linear motor can still work.

5.2 *Direction of development – lay-out solutions*

Nowadays trend of hydraulics aims into combination of power advantages of hydraulics and smart management from electronic devices [Lovrec 2008], [Manasek 2002], [Lisowski 2021]. Electrohydraulics opens new possibilities and simple solutions [Sakurai 2002], where dimensions are reduced, management logic of the whole system is concentrated into one managing system but still the power of hydraulics is preserved. Also efficiency of the system can be improved behalf of that [Siebert 2017], [Wu 2003].

With the knowledge of rotary pressure intensifier's behaviour from chapter 4 and wide area of utilization described in chapter 5, it would be meaningful to think about transforming rotary flow divider into compact device which would be also able to react to outer signals and commands and dispone with the ability to be part of circuit's managing system without any additional electrohydraulic components.

The first solution transforms rotary flow divider into rotary pressure intensifier as it is seen in Figure 11. It is based on two-section rotary flow divider. This device has only one output, one input and the drain, which is combined from right section output and the drain for leakage. The idea is to use bypass when no intensified pressure is needed. Then the gearing would not be in motion and there would be no mechanical losses emerging from it. In addition the servise life would be increased when gearing won't be running the whole worklife of device.

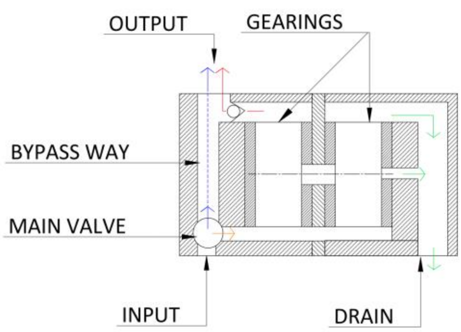

Figure 11. Intensifier with bypass and high/low pressure mode

In mode of pressure multiplication the main valve (directional valve, pressure valve or other) will direct the input delivery to go through the gearing. Multiplied output from the first (left) section is the output of the whole device. Output of the second (right) section is connected with the leakage drain into one common device drain. According to flow rate from the drain output, there can be plugged another branch or device with low pressure requirement. There would be still pressure multiplication but the current values would have to be calculated with this additional pressure as the general equation 2 shows.

Main valve regulating direction of the flow offering a possibility for the intensifier to be direct part of the communication with the rest of the system (Figure 12).

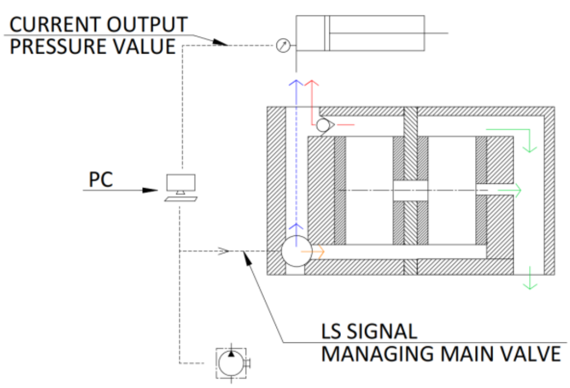

Figure 12. Pressure intensifier as the part of the communication

This device is ready to cooperate with load-sensing signal, which can determine mode in which the intensifier works. So, when higher pressure is needed load-sensing signal will switch the main valve to change the direction from the first mode, where delivery goes through bypass, to the second multiplying mode, where delivery goes through the gearing.

Signal changing intensifier's mode could be also determined by position, where the device starts to multiply depending on defined position of a final appliance. Or any other signals.

There is no need to unconditionally insist on electronic signal managing the main valve. In Figure 13, there is to be seen a hydraulic load-sensing solution, where the pilot pressure way is integrated into the intensifier, so the work mode is self sufficient without outer input.

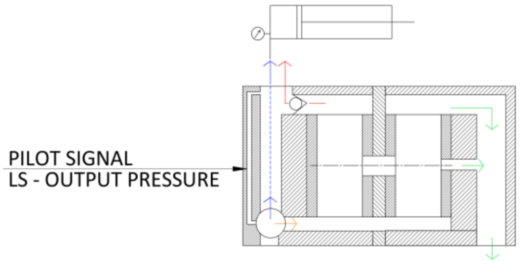

Figure 13. Intensifier with pilot pressure signal

So based on output pressure intensifier itself decides when to go through bypass and when through gearing (and multiply pressure). In this purely hydraulic solution, there is unfortunately not a possibility to manage a work mode via appliance position or else.

The idea of integrated main valve responsible for running mode of an intensifier can be also applied in extension of gear pump and pressure intensifier assembly from Figure 9. There is a possibility to expand and use middle body connecting gear pump and rotary flow divider and integrate there a valve which would manage if the output from this assembly device run at high pressure mode, where the intensifier is working or low pressure mode, where delivery from the pump goes through the middle body directly to the circuit.

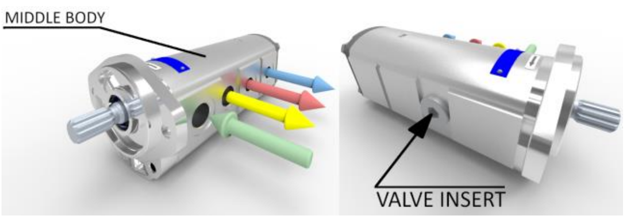

Figure 14. Compact assembly high/low pressure mode

This compact solution, pictured in Figure 14, has ability to decide when to work as gear pump alone and do not add intensifier. Green arrow represents input flow direction. Yellow arrow is active output when low pressure mode is on, so it symbolizes direct delivery from the pump, in this mode red and blue outputs are not active. Red arrow represents pressure multiplied output delivery in high pressure mode. In this mode yellow output is closed and output with blue arrow is active as the drain. The main valve would be insert in middle body on the other side than outputs to control the direction of the flow.

That mode results less friction losses and longer lifelong. Or when there is a need to multiply for required output pressure based on the information on the main valve. This information could be electric or hydraulic (pilot pressure) as in previous solutions demonstrated on Figure 12, 13. This lay-out version could be also customized when needed, for example drain represented with blue arrow could aim from the cover, there is also a possibility to insert input from the other side than it is pictured in Figure 14.

6 CONCLUSION

Rotary flow dividers are usually used for hydraulic motors synchronization. In this application all divider's outputs are under the load. It is also possible to use rotary flow divider as pressure intensifier. When there is one section output pressure multiplied and others are plugged to the tank without load. To evaluate this new kind of loading new evaluation methodology including creation of new pressure multiplying efficiency was developed and described in article presented via publishing house MDPI [Hradecky 2022].

Based on this evaluation methodology, extensive experimental testing was done on many samples of rotary flow dividers of different designs, section volumes and materials. There was two-section, three-section and asymmetric dividers tested.

The results were characteristics of pressure multiplying efficiency and values of flow dividing inaccuracies. Based on these results favored types of dividers as pressure intensifiers were chosen. Then the long-term measurement on maximum pressure 400 bar was done and was proven, that divider used as pressure intensifier can be used in long period of time to deliver multiplied pressure 400 bar.

According to advantages of pressure intensifier based on the concept of rotary flow divider, which are compact dimensions, easy to dimension in relationship to input flow rate of final appliance and, the main one, ability of continuous run, there was a whole new area of utilization revealed. There were alternatives to flow regulation, piston pumps or flow regeneration suggested and described.

Finally, there were new lay-outs of pressure intensifiers showed. Firstly, as new device working in two (low pressure and high pressure) modes via bypass prepared for load-sensing control in connection with electronic or hydraulic (pilot) signal. There is also a possibility to use other outer signal in case of electronic management as position control or other.

Then there was a lay-out of compact assembly of gear pump and pressure intensifier introduced, which is capable of run at low pressure mode without using pressure intensifier and high pressure mode where output pressure is multiplied.

The result of working at high and low pressure modes are energy savings via mechanical losses and also long life term.

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