MODEL TESTING OF THE INTERNAL LEAKS OF VALVE BODY IN AUTOMATIC TRANSMISSION

Tadeusz Dziubak

Military University of Technology, Faculty of Mechanical Engineering
Gen. Sylwestra Kaliskiego Street 2, 00-908 Warsaw
tel.: 261 837 121, fax: +48 22 6837370
e-mail: tadeusz.dziubak@wat.edu.pl

Paweł Szczepaniak

Air Force Institute of Technology
Ksiecia Boleslawa Street 6, 01-494 Warsaw
tel.: +48 22 6851300, fax: +48 22 8364471, e-mail: pawel.szczepaniak@itwl.pl

Abstract

The article presents the working conditions and the functions of the ATF fluid in an automatic transmission. It was noted that the correct operation of the automatic transmission is heavily influenced by the quality of the ATF fluid, which operates in disadvantageous conditions of oxidising environment, is subject to contamination and undergoes intense shearing, thus changing its physical and chemical properties during use. The analysis included the disadvantageous, from the point of view of loss of fluid pressure in the automatic transmission's hydraulic system, phenomenon of the fluid's flow through fractures (clearances) of the hydraulic precise pairs "called the rate of flow through internal leaks" or an "internal leak". The model of the rate of flow through internal leaks was proposed to determine the impact of the precise pairs' wear and the hydraulic fluid's properties on the aggregated leaks in the hydraulic system controller of the automatic transmission. The modelling utilised the dependency between the rate of flow through internal leaks of the hydraulic precise pair and the coaxial circular fracture. The model's assumptions were formulated. The values of clearances of the electrohydraulic controller's precise pairs were determined during the measurements of the actual structure – based on the automatic transmission's mileage. The measurements featured relevant diameters of pushers and sliders, as well as internal diameters of cylindrical openings of manifold sliders and hydraulic suppressors. Variant model testing was conducted with various degrees of the fluid's wear and temperature (viscosity and density) for conditions of driving with transmission "1" and "2".

Keywords: automatic transmission, hydraulic system, hydraulic precise pair, wear of hydraulic couplings, internal leaks, ATF fluid flow rate model

1. Introduction

An automatic transmission is an assembly with a very complex structure. Control of automatic transmission is executed via a complex hydraulic system. The electrohydraulic controller includes tens of manifold elements. Each manifold element can have up to several precise pairs: slide pusher – cylindrical casing, constituting a coupling. The wear of the automatic transmission's hydraulic system elements and ageing of the fluid occurring during operation negatively affect the system's technical conditions, which is manifested in the deviations of the system's technical parameters [5-9]. The correct pressure of the ATF fluid is the condition for effective functioning of the hydraulic control system, which in turn ensures the correct operation of the automatic transmission. The quality of the ATF fluid is also very important for the correct operation of the transmission. It operates in disadvantageous conditions of oxidising environment and undergoes intense shearing, thus its physical and chemical properties are subject to change during use [1, 3]. The ATF fluid's lowered kinematic viscosity in comparison to the viscosity of a new fluid is the

reason for increased rate of flow through internal leaks of the precise pairs of the electrohydraulic controller's manifold elements and other pressurised seals and couplings. At a certain stage of the automatic transmission's operation and in specific conditions of the vehicle's motion, there is a possibility of occurrence of a phenomenon, during which the demand for a stream of work fluid exceeds the capacity of the hydraulic pump. The purpose of the article was to assess the impact of increased clearance (wear) of the precise pairs of the manifold elements and the loss of fluid viscosity on the ATF fluid's rate of flow through internal leaks of the electrohydraulic controller.

2. Hydraulic fractures

Within moving connections between two interoperating parts, e.g. between a pusher and cylinder, there is space affected by a specific assembly (radial) clearance referred to as a fracture. The break-in process and then the wear during operation result in the increase of clearances, hence the increase of the fracture's thickness [14, 19].

During the use of the hydraulic assembly, the clearance of the hydraulic precise pair increases. The value of the clearance consists of the assembly clearance and the increase in clearance resulting from the operating abrasive wear of the coupling's precise elements:

$$c_r = c_m + \Delta c_e \text{ [mm]}, \tag{1}$$

where: c_m – radial assembly clearance [mm], Δc_e – increase in the radial clearance resulting from the abrasive wear during operation [mm].

The characteristic wear of the elements of hydraulic precise pairs includes the following [21]: adhesion – welding of the elements of surfaces in contact with one another (locking of the slider in the sleeve), abrasion – abrasion of contacting surfaces of the slider and sleeve's hydraulic precise pairs' elements (basic wear) and pitting – corrosive and fatigue wear.

The impact of the thermal expansion of the hydraulic precise pairs' elements is substantial because the operating temperature T_e of the ATF fluid and transmission elements is within the range of 70-90°C. The difference in temperatures ΔT between the radial clearance measurement temperature c_r (conducted at the ambient temperature $T_o = 20°C$) and the temperature of the hydraulic precise pairs' elements during operation must amount to 70°C. Due to the above, the dependency of the effective radial clearance of the hydraulic precise pair (c_{re}) has the following form [11, 12]:

$$c_{re} = c_r + \Delta c_{Tk} - \Delta c_{TS} = c_r + \left(\frac{(\beta_k \cdot D_k \cdot \Delta T_k) - (\beta_S \cdot d_S \cdot \Delta T_S)}{2}\right) \text{ [mm]}, \tag{2}$$

where: Δc_{Tk}, Δc_{TS} – change in the clearance resulting from the thermal expansion of the controller body and the manifold slider, respectively [mm], β_k, β_S – linear thermal expansion index of the body and slider material, respectively [1/°C], D_k, ds – diameter of the opening in the body and the manifold slider, respectively [mm], ΔT_S, ΔT_S – difference in temperature between the actual temperature during operation of the body and manifold slider, respectively, and the temperature of these elements during measurement.

3. Leakage in an automatic transmission

The mobility-based fitting of precise pairs of the hydraulic control system's manifold elements must include assembly clearances. The break-in process and then wear during operation result in the increase of the clearances. Due to the differences in the hydraulic fluid's pressure on both sides of the hydraulic fracture, there is a disadvantageous, from the point of view of losses in stream, phenomenon of fluid flow through the fracture (clearance) of the precise pair's coupling referred to as the rate of flow through internal leaks or an "internal leak" [19]. The hydraulic system of an automatic transmission includes many couplings, which feature the undesired flow of the ATF

fluid (internal leak). The total number of leaks in all elements of hydraulic precise pairs taking part in the execution of a specific function of the system is referred to as the aggregated rate of internal leakage of the electrohydraulic controller. In specific conditions of the vehicle's motion, due to large fluid losses through the leaks of the precise pairs, there is possibility of occurrence of a phenomenon that increases the demand for the work fluid stream above the capacity of the hydraulic pump. An internal leak in the fracture also has its advantages. A minimum fluid leak in the friction area provides lubrication of the hydraulic precise pair's elements. The flow is laminar and the flow rate depends on the geometrical size of the fracture and the properties of the hydraulic fluid. The modelling utilised the equation of internal leaks q_{ve} for the hydraulic precise pair with a coaxial circular fracture according to Blackburn J. F., Reethof G. and Shearer J. L [19]. Fig. 1a presents the diagram of the hydraulic precise pair with a coaxial circular fracture and the distribution of pressure in the fracture's transverse and longitudinal directions (Fig. 1b).

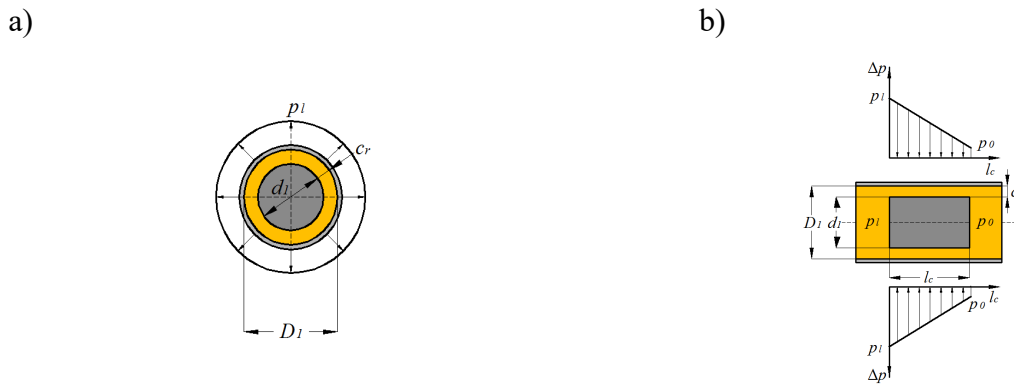a)   b)

Fig. 1. Diagram and distribution of the pressure in a hydraulic precise pair with a coaxial circular fracture: a) in the fracture's transverse direction, b) in the fracture's longitudinal direction, D_l – internal diameter of the cylindrical part, d_l – slider diameter, c_r – radial clearance (fracture thickness), l_c – slider length, p_l – pressure in the fracture, p_0 – pressure in the fracture [19, 21]

The general equation of the flow through internal leaks of the automatic transmission controller's hydraulic precise pair takes the following simplified form:

$$q_{ve} = 10^6 \cdot \frac{(p_l - p_0) \cdot \pi \cdot d_1 \cdot c_r^3}{12 \cdot v \cdot \rho(0) \cdot l_c} \ [\text{mm}^3/\text{s}], \tag{3}$$

where: p_l – pressure on the supply side [kPa], p_0 – pressure on the leak side [kPa], $(p_l - p_0)$ – loss of pressure in the fracture [kPa], d_1 – diameter of the hydraulic precise pair's element (roller) [mm], c_r – radial clearance of the hydraulic precise pair [mm], $\rho(0)$ – hydraulic fluid density at atmospheric pressure[g/cm³], v – kinematic viscosity [mm²/s], l_c – length of contact of the precise pair [mm].

In the case of narrow fractures with the radial clearance of 4-20 μm (capillary), there is a phenomenon of obliteration. For fractures larger than 20 μm, the phenomenon of obliteration practically does not occur and it can be omitted in the calculations [21].

4. Mathematical model

Currently, one of the research tools used increasingly in the analysis of the work processes in hydraulic elements is the mathematical modelling [20]. The assessments of the impact of wear of the precise pairs of the automatic transmission's hydraulic system on the rate of flow of the ATF fluid through internal leaks can be made on the basis of the analysis of the results of the model testing of internal leaks of the automatic transmission's electrohydraulic controller. The value of internal leaks is information allowing for the determination of the specific part of the instantaneous capacity of the hydraulic pump that is lost in the flow through internal leaks of the electrohydraulic

controller. The development of the structural models (Fig. 2) for the executed transmissions is based on separating from the model of the automatic transmission's electrohydraulic controller of the elements, which at the given time are in contact with the pressurised hydraulic fluid. These structures can be described mathematically in the scope of internal leaks for specific precise pair couplings of the given hydraulic element.
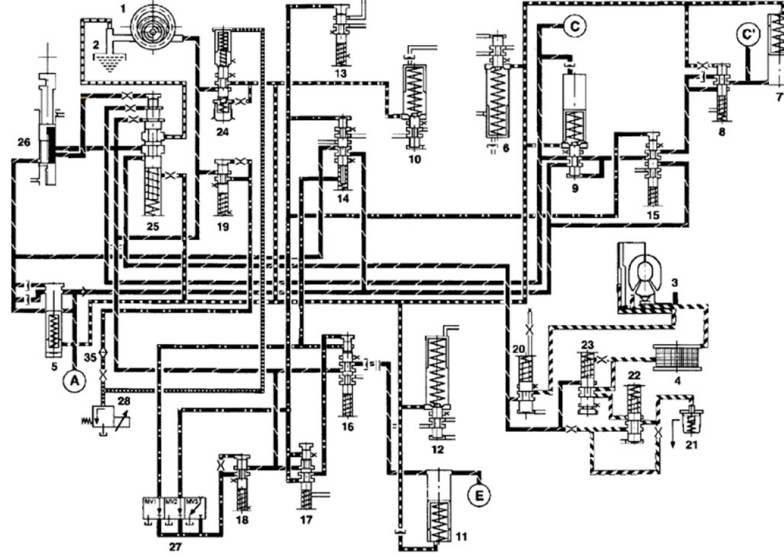

Fig. 2. Structural model of internal leaks of an electrohydraulic controller in an automatic transmission during the execution of second transmission [10]

The modelling of the electrohydraulic controller's internal leaks featured the consideration of the stationary states of the position of the manifold valve sliders and the impact of the thermal expansion of materials on the radial clearance in the hydraulic precise pair (effective clearance c_e), while the fracture obliteration was omitted. The structural methods take into consideration the methods of hydraulic fluid supply and the position of the manifold sliders in the electrohydraulic controller's body. This can be used as the basis for describing the aggregated internal leak of the hydraulic precise pair with utilisation of the mathematical dependency. During the execution of the second transmission, the aggregated leak of the hydraulic system takes the following form:

$$\Sigma q_{D/2} = \Sigma q_{p_{g2}} + \Sigma q_{p_{s_2}} + \Sigma q_{p_{m_2}} + \Sigma q_{p_{k_2}} \ [\text{mm}^3/\text{s}], \tag{4}$$

where: $\Sigma q_{p_{g2}}$, $\Sigma q_{p_{s_2}}$, $\Sigma q_{p_{m_2}}$, $\Sigma q_{p_{k_2}}$ – aggregated leak in the supply section with subsequent pressures: main, control, modulated and converter pressure.

During the execution of the second transmission, the equation of the aggregated leak for the section supplied with main pressure p_g for hydraulic suppressors ($i = 5, 7, 11$) and manifold valve sliders ($i = 8, 9, 14, 15, 16, 17, 20, 23, 25, 26$):

$$\Sigma q_{p_{g2}} = \Sigma q_{p_{g2}5} + \Sigma q_{p_{g2}7} + \Sigma q_{p_{g2}11} + \Sigma q_{p_{g2}8} + \Sigma q_{p_{g2}9} + \Sigma q_{p_{g2}14} + \ \Sigma q_{p_{g2}15} + \Sigma q_{p_{g2}16} +$$

$$+ \Sigma q_{p_{g2}17} + \ \Sigma q_{p_{g2}20} + \ \Sigma q_{p_{g2}23} + \Sigma q_{p_{g2}25} + \ \Sigma q_{p_{g2}26} \ [\text{mm}^3/\text{s}], \tag{5}$$

For example, the equation of the aggregated leak of the supply side with main pressure for the *"8"* diverter valve during the execution of the second transmission is as follows:

$$\Sigma q_{p_{g2}8} = q_{p_{g2}8-1} + q_{p_{g2}8-2} = (10^6 \cdot \frac{(p_g - p_m) \cdot \pi \cdot d_{1-8} \cdot c_{re1-8}^3}{12 \cdot \upsilon \cdot \rho(0) \cdot l_{c1-8}}) +$$

$$+ (10^6 \cdot \frac{(p_g - 0{,}1 \cdot p_g) \cdot \pi \cdot d_{2-8} \cdot c_{re2-8}^3}{12 \cdot \upsilon \cdot \rho(0) \cdot l_{c2-8}}) \ [\text{mm}^3/\text{s}]. \tag{6}$$

The determination of essential features and properties of the test subject required its decomposition and conducting a series of measurements, including element diameter measurements. These measurements were the basis for calculating the radial clearance c_r of the hydraulic precise pairs.

5. Analysis of the results of testing the controller's internal tightness model

The calculations of internal leaks through the controller's hydraulic precise pair couplings were conducted for several variants of the ATF fluid's temperatures and the degrees of wear of the controller's elements. The change in the temperature T_e of the hydraulic fluid contributes to the change in the following input values constituting data for calculating the rate of flow $\sum q_i$ of the ATF fluid through internal leaks: kinematic value v and density ρ of the hydraulic fluid and the effective radial clearance c_{re}. Tab. 2 presents the modelling variants of internal leaks through the electrohydraulic controller's hydraulic precise pair couplings. In the first variant (**W1**), it was assumed that the operating temperature of the hydraulic fluid amounts to 80°C, while the effective radial clearance c_{re} in the hydraulic precise pairs has the values determined during measurements on the actual structure (with consideration of the impact of the ATF fluid's temperature) and kinematic viscosity of a new ATF fluid. In the second variant, (**W2**) kinematic viscosity v was changed to the value obtained during measurements for the oil sample after the mileage $S = 106315$ km [7]. In comparison to the first variant (**W1**), the third variant (**W3**) has increased radial clearances in all hydraulic precise pairs of the controller by the arbitrary degree of wear $z_a = 10\%$. Variants from (**W4**) to (**W8**) feature increased radial clearances of all hydraulic precise pairs of the controller and the arbitrary degree of wear $z_a = 50\%$. The arbitrary degree of wear z_a was defined for the purpose of modelling the impact of the clearance (potential wear) on the internal leaks of the hydraulic controller. The arbitrary degree of wear z_a determines the percentile increase in the radial clearance of the hydraulic precise pair in relation to the clearance determined on the basis of measurements and calculations of the diameters of sliders (pushers) d_i and sleeves D_i in the hydraulic controller's body. The radial clearance of the controller's precise pair increased by the degree of wear z_a determines the following dependency:

$$c_{r(i)\,z_a\%} = \frac{(D_i - d_i)}{2} + \frac{z_a}{100} \cdot c_{r(i)} \text{ [mm]}, \tag{7}$$

The modelling tests featured an increase in the radial clearances of all hydraulic precise pairs of the hydraulic controller by the arbitrary degree of wear z_a in relation to clearances determined based on the measurements. The modelling of the ATF fluid properties in terms of $T_e = -40\text{-}100°C$, which for the tested automatic transmission should have the specification DEXRON ATF IID [10, 15, 18], was conducted using the data from the safety data sheet of HIPOL ATF IID [17]. When determining the changes in the kinematic viscosity v and density ρ of the ATF IID fluid including the temperature, we used the charts and dependencies from [13, 16]. The results of the model testing in the form of calculations of the aggregated internal leaks of couplings of the automatic transmission's ZF4HP-24 controller in the conditions of attempting acceleration (driving with transmission "1", acceleration, change "1→2", driving with transmission "2") lasting for $t_p = 9$ s were presented in Fig. 9 and 10 as well as in Tab. 1. The process of changing the gear "1→2" starts at $t_p = 3.5$ s and ends after the approximate time $t_p = 4.8$ s, which in the chart is visible in the form of a rapid (to 33 dm^3/min) increase in the pump's performance Q_p during acceleration with transmission "1". After activating transmission "2" ($t_p = 4.8$ s) is stabilised at around 33 dm^3/min because the acceleration is done with transmission "2". The nature of leak changes in the entire scope of values depends on the course of the main pressure p_g in the hydraulic system. The scope of values of the operating changes in the main pressure p_g in the hydraulic system of the tested automatic transmission, depending on its energising, amounts to 400-900 kPa (0.4-0.9 MPa) [5, 7]. The course was obtained during testing and implemented in the form of input data for the model

tests. Regardless of the modelled operation variant of the electrohydraulic controller, the internal leaks through hydraulic precise pair couplings change gradually throughout the entire testing period $t_p = 9$ s, but are maintained at a specific average level.
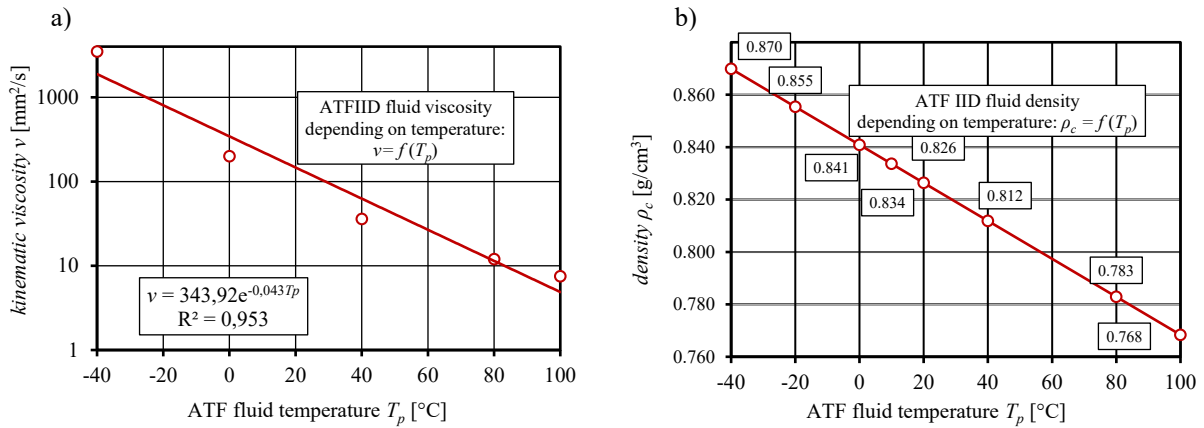

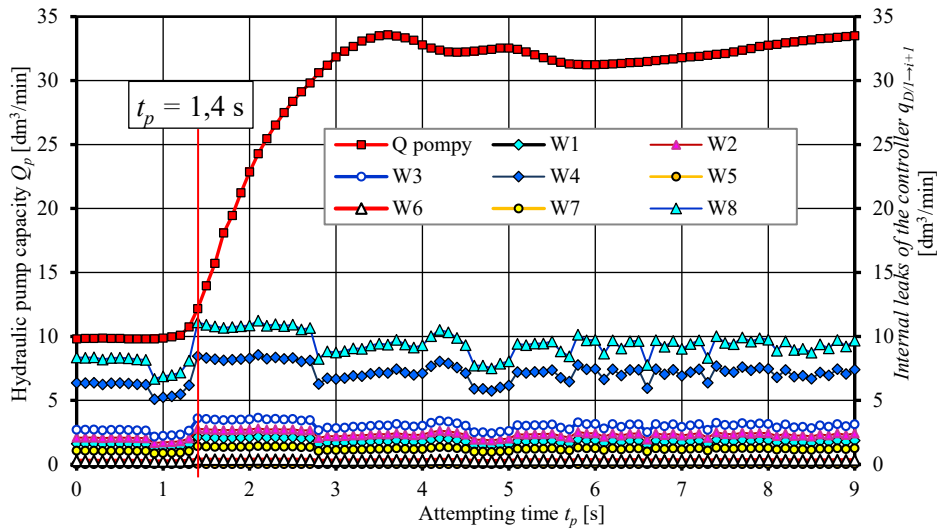*Fig. 3. Properties of the ATF IID fluid depending on temperature: a) kinematic viscosity v, b) density ρ [2, 4, 16]*

Fig. 4. Specification of the rate of flow through internal leaks $q_{D/1\rightarrow i+1}$ of the electrohydraulic controller for the conditions of attempting acceleration with transmission "1" and "2" – calculation variants: W1-W8

Tab. 1. Results of the model testing of internal leaks in the hydraulic controller for the following conditions: driving with transmission "1", acceleration, changing the transmission "1→2", driving with transmission "2"

Variant no.	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**
ATF fluid temperature: T_e [°C]	80	80	80	80	-40	20	40	100
Kinematic viscosity v [mm²/s]	11.1	11.1	11.1	11.1	1,922.7	145.5	61.5	4.65
Density: ρ_c [g/cm³]	0.783	0.783	0.783	0.783	0.870	0.826	0.812	0.768
Arbitrary wear z_a [%]	0	0	10	50	50	50	50	50
Value of internal leaks $q_{D/1\rightarrow i+1}$ [dm³/min]	**0.9-2.16**	**1.67-2.81**	**2.16-3.64**	**5.09-8.46**	**max. 0.021**	**max. 0.38**	**max. 1.41**	**6.67-11.23**
Hydraulic pump capacity [%]	**17.7**	**23.1**	**29.9**	**69.5**	**0.172**	**3.12**	**11.6**	**92.2**

For variant W6, the average value of internal leaks through hydraulic precise pair couplings amounts to $g_D = 0.32$ dm³/min, while for variant W3 – $q_D = 3.2$ dm³/min and for variant W8 – $q_D =$

9.3 dm^3/min. Fig. 9 demonstrates that the critical period of operation of the electrohydraulic controller lasts until $t_p = 1.4$ s. The pump's performance increasing (from $t_p = 1$ s) along with the motor's rotations reaches $Q_p = 12.18$ dm^3/min., i.e. slightly higher than the internal leaks through the hydraulic precise pair couplings occurring in this time. For variant W8, the value amounts to $q_D = 11.2$ dm^3/min. and for variant W4 – $q_D = 8.46$ dm^3/min. The values of internal leaks through the hydraulic precise pair couplings increase along with the increase in the fluid's temperature and wear of the precise pairs – increase in the radial clearance. The increase in the hydraulic fluid's temperature in the range of -40-+100°C (decrease in viscosity) and the temperature of the hydraulic precise pair elements takes place, with the same degree of element wear ($z_a = 50\%$), along with the increase in the internal leaks through the couplings, except that a substantial increase takes place after exceeding the fluid's temperature $t_p = 40$°C (Fig. 10). After reaching the fluid's temperature $t_p = 100$°C, the rate of flow of internal leaks through the hydraulic precise pair couplings increases tenfold and is within the range of $q_{D/l} = 6/.67$-11.23 dm^3/min, which constitutes over 92% of the hydraulic pump's performance Q_p for the test time $t_p = 1.4$ s. For the same value of the hydraulic fluid's temperature ($T_e = 80$ºC), the value of internal leaks is determined by the wear of the hydraulic precise pairs' elements. The increase in the couplings' degree of wear z_a takes place along with the increase in internal leaks and for $z_a = 50\%$, their value increases fourfold and amounts to $q_{D/l} = 5.09$-8.56 dm^3/min, which constitutes over 70% of the hydraulic pump's performance Q_p.
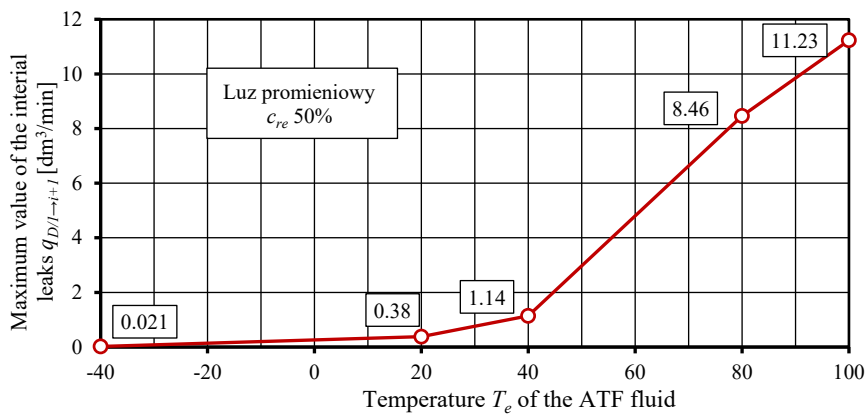

Fig. 5. The maximum value of the rate of flow $q_{D/l \rightarrow i+1}$ through internal leaks of the electrohydraulic controller depending on the temperature T_e of the hydraulic fluid for the following conditions: driving with transmission "1", accelerating, transmission switch "1→2", driving with transmission "2", with the assumption of wear of the hydraulic precise pair's coupling (50% increase in the radial clearance c_{re})

Conclusions

The purpose of the model testing was to determine the impact of abrasive wear of the electrohydraulic controller elements surfaces and the hydraulic fluid's temperature T_e on the rate of flow $q_{D/l \rightarrow i+1}$ through internal leaks in the hydraulic precise pairs of an electrohydraulic controller. The obtained results of the model testing and the conducted analyses allowed formulating the following conclusions:
1. The electrohydraulic controller includes tens manifold elements and each element can have up to several precise pairs: slide pusher – cylindrical casing, constituting a coupling. In the fractures (gaps) of the hydraulic precise pair couplings, due to the difference in the hydraulic fluid's pressure on both sides of the hydraulic fracture, there is a disadvantageous, from the point of view of stream losses, phenomenon of fluid flow referred to as the rate of flow of the internal leak or "internal leak".
2. The increase in the fluid's temperature, decrease in viscosity and increase in the wear of the precise pairs take place along with the increase in the internal leaks through the hydraulic

precise pair couplings, which causes a loss in main pressure p_g below the value required for the correct operation of the automatic transmission's hydraulic control system.

3. The increase in the ATF hydraulic fluid's temperature T_e (loss in viscosity) and the temperature of the hydraulic precise pair elements with their constant wear causes an increase (in leaks) of the rate of flow through internal leaks, except that the substantial increase takes place only after exceeding the fluid's temperature $t_p = 40°C$. After reaching the fluid's temperature $t_p = 100°C$, the rate of flow of internal leaks through the hydraulic precise pair couplings increases several times and can be the cause of loss in main pressure p_g below the value required for the correct operation of the electrohydraulic controller.

4. The highest values of internal leaks in the electrohydraulic controller's hydraulic precise pairs occur in the case of high wear ($z_a = 50\%$) and during operation in high temperature. The internal leaks then constitute a substantial part (even 92%) of the hydraulic pump's instantaneous performance Q_p.

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