

# The use of various types of circulation in the design of excavator hydraulic drive

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**Abstract:** This article is devoted to the review, study and analysis of the existing types of circulation used in the design of hydraulic drives of construction machines. Three main types of circulation are distinguished: closed, open, and semi-closed. A comparison is given and the characteristic features of each of them are described. Particular attention is paid to semi-closed circulation because it is under investigated. The sequence of movements of the equipment elements during the work cycle is shown. The results are presented, in the form of a diagram of flow rates in the actuators of an excavator planner, made by semi-closed circulation. This work will be of interest to specialists in the field of designing volumetric hydraulic drives of construction vehicles.

## Introduction

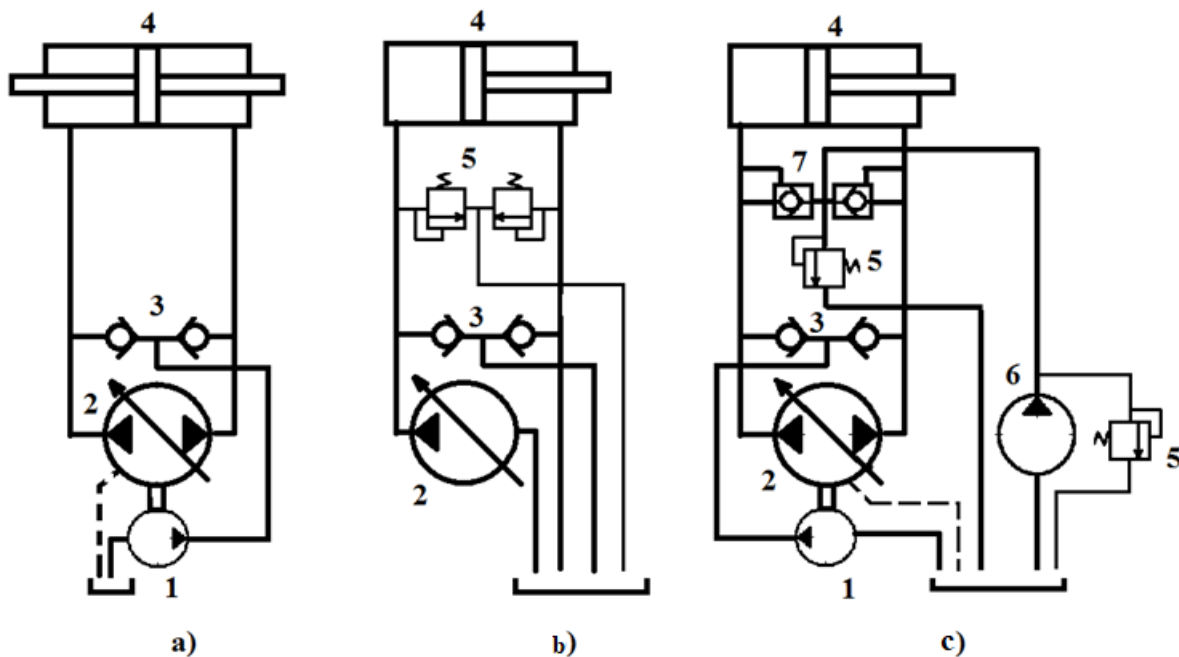
Excavators are multi-engine machines with a rigid suspension of working equipment, in which a hydraulic volumetric drive is used to transfer power from the engine to the working mechanisms. Compared to mechanical, hydraulic excavators have a wider range of interchangeable work tools, a greater number of main and auxiliary movements of the working equipment, which significantly expands their technological capabilities.

The hydraulic drive allows [1,2]: to significantly simplify the kinematics of the transmission and working equipment; expand the range of interchangeable work tools; reduce the size of the machine; rationally combine work operations; maximize the power of the power plant; increase the mobility and versatility of machines and improve the quality of work performed; ensure smooth movement and precise orientation of the work tool; realize great digging efforts; improve machine performance.

Fig. 1 shows various types of circulations used to create the hydraulic drive of construction vehicles. When creating hydraulic circuits for hydraulic machines, the first two types of circulation are widely used [3].

A feature of the closed circulation circuit is the work on the hydraulic mechanism, which has the same volume of cavities, in the case of using a hydraulic cylinder with a two-sided rod or a hydraulic motor. The flow rate diagram for a circuit made by closed circulation is shown in Fig. 2a. Make-up is provided by a make-up pump 1, this pump also compensates for leakage in the hydraulic machine and the actuator. When the rod moves, the flow displaced from the cavity of the hydraulic cylinder enters the suction of the pump minus volume losses in the pump [4,5].





**Figure 1.** Types of circulation

a) — closed circulation; b) — open circulation; c) — semi-closed circulation; 1 — make-up pump; 2 — the main pump; 3 — make-up valves; 4 — a hydraulic cylinder; 5 — safety valves; 6 — pump compensating for the lack of working fluid in the cavity of the differential hydraulic cylinder

A feature of the circuit with open circulation is the difference in the volume of the piston and rod cavities of the hydraulic cylinder, which is determined by the coefficient:

$$\varphi = \frac{S_P}{S_R};$$

where,  $S_P$  — the area of the piston cavity of the hydraulic cylinder;

$S_R$  — the area of the rod cavity of the hydraulic cylinder.

The pump draws liquid from the tank, and the liquid is also drained into the tank, so this scheme is most often used for machines in the hydraulic drive of which several differential hydraulic cylinders are used. For example, in excavators, where differential hydraulic cylinders are used in the mechanisms of the shovel boom, handle and bucket: in the drive of the mechanism for lifting the shovel boom and telescoping. In the hydraulic drive of excavators, secondary valves (Fig. 1b, pos. 5) are used to protect the drive and metal structures, which protect the drive and the metal structure from overload, in the case when, for example, the excavator handle mechanism loads the locked cavity of the boom or bucket hydraulic cylinders while digging [6, 7]. When the valve is activated in the rod cavity, the piston moves and the rod extends, since the fluid is drained through the valve. Since the hydraulic cylinder cavities are locked, the piston cavity is fed by gravity from the tank through the check valves Fig. 1b pos. 3, due to the difference between the pressure in the tank and the pressure in the cavity.

The flow rates diagram for the scheme made by open circulation is shown in Fig. 2b. When the rod is extended, the pump feed enters the piston cavity, the discharge rate from the rod cavity is less than the pump feed, due to the difference between the areas of the piston and rod cavities [8].

$$Q_D < Q_P = Q_{PUMP};$$

$$Q_D = Q_R = \frac{Q_P}{\phi};$$

When retracting the rod, the flow rate entering the drain is greater than the flow rate entering the rod cavity.

$$Q_D > Q_R = Q_{PUMP};$$

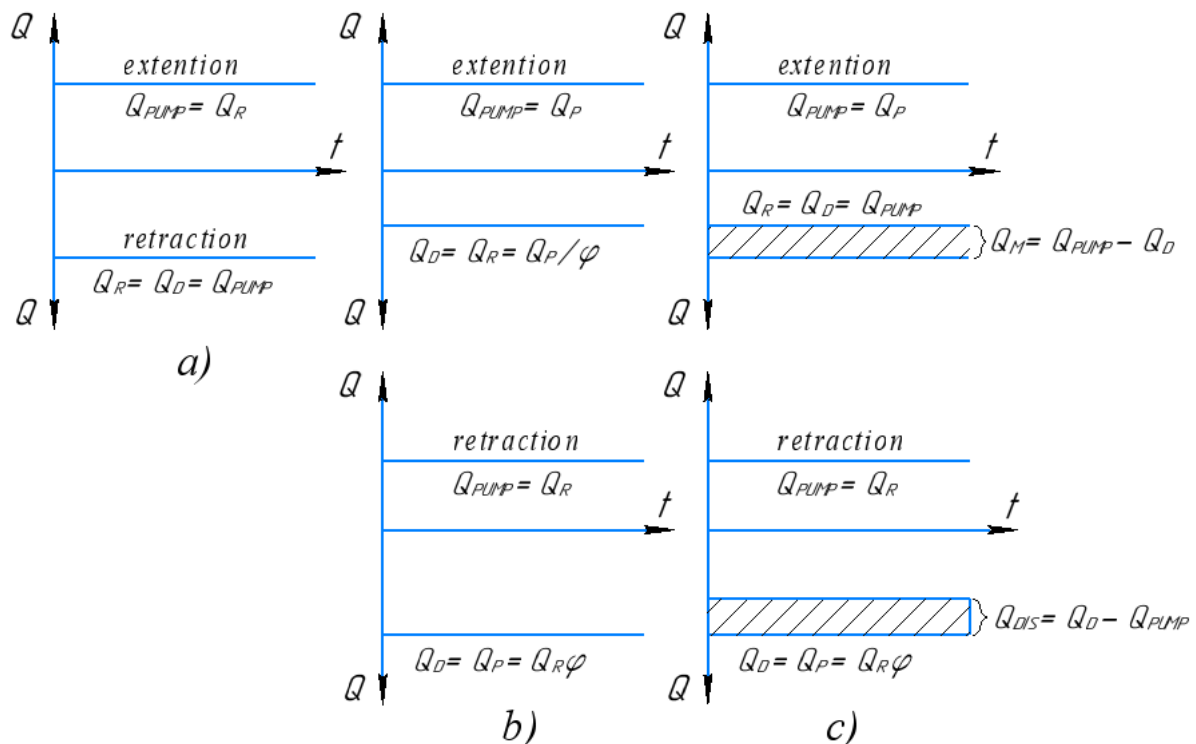
$$Q_D = Q_R \cdot \phi;$$

Fig. 1c shows a circuit made by semi-closed circulation. The pump, designed to work in closed circulation, is used to drive a mechanism with a differential hydraulic cylinder. And the difference in the volume of the piston and rod cavities necessitates the introduction of additional devices [9,10].

When the rod is extended, Fig. 2c, a pump feed is supplied to the piston cavity, and a smaller volume of liquid is supplied from the rod cavity to the suction, the difference in these rates is compensated by an additional pump operating in open circulation and performing, in addition to compensation, other functions in the drive. When the rod is pulled the pump feed is supplied into the rod cavity, and a larger volume of liquid is drained from the piston cavity, the difference in these rates is dumped into the tank so that the balance of rates on the pump operating in a closed circulation remains unchanged.

Despite the complication of the hydraulic circuit used for semi-closed circulation, it is used, for example, on Slovakian excavators, which are widely used in the CIS [11,12].

To control the drive speed in open circuits, throttling hydraulic valves are used; in semi-closed circuits, speed is controlled by changing the pump's working volume, which is more energy-efficient than throttling [13,14].



**Figure 2.**Diagrams of fluid supply to the piston cavity and drain from the rod cavity  
a) closed circulation; b) open circulation; c) semi-closed circulation;  $Q_R$ — flow rate into the rod cavity,  $Q_P$ — flow rate into the piston cavity,  $Q_{PUMP}$ — pump supply,  $Q_D$ — drainage flow rate,  $Q_m$ — make-up flow rate,  $Q_{DIS}$ — discharge flow.

### The sequence of movements of the elements of the working equipment during the work cycle

In the work cycle, the sequence of operations of the excavator planner can be divided into two groups of operations. Digging: by turning the bucket or moving the telescope. Transport operations: lifting the working equipment from the bottom, turning the bucket to keep soil in the bucket, turning from the bottom, unloading, turning into the bottom, lowering the working equipment, installing the bucket at a new digging point [15].

Duty cycle operations can be performed without combining the movements of mechanisms or with combining, for technological reasons, as well as to reduce the duration of the cycle. Some operations, for example, planning slopes or planning the bottom cannot be performed without combinations. Combining operations gives the operator more opportunities, and therefore, when creating hydraulic circuits for excavators, the need to combine the movements of mechanisms is always taken into account.

The table below lists possible combinations of movements of mechanisms of six elements in two, which usually tend to ensure the use of a dual-pump circuit [16].

**Table 1.** Combination of movements of six mechanisms in two movements

Mechanism	Telescope	Bucket	Boom	Rotation	Movement
Telescope		"+"	"+"	"+"	"+"
Bucket	"+"		"+"	"+"	"+"
Boom	"+"	"+"		"+"	"+"
Rotation	"+"	"+"	"+"		"+"
Movement	"+"	"+"	"+"	"+"	

When digging, the movements of the bucket and telescope do not combine, since before digging, when turning the bucket, the cutting angle is set, which does not change during digging. If digging is done with a bucket, it is also possible to combine with a boom to reduce the thickness of the chips. And it is also possible that, when digging, the movement of the telescope is combined with the turn of the bucket for processing slopes.

The movement of the boom is combined with rotation during transport operations, with the movement when pulling the machine from the ground when working in viscous water-saturated soils.

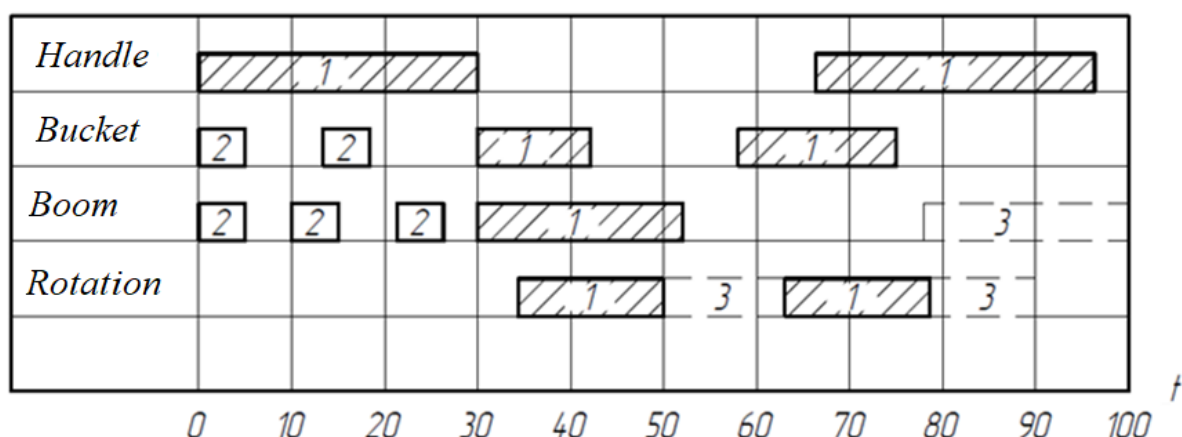
Excavation of the soil with telescopic working equipment with a backhoe bucket can be done both by turning the bucket and retracting the movable boom sections.

With above information, the retraction mechanism is considered the main, and the bucket rotation mechanism is considered auxiliary. The latter can dig weak soils, cut the bucket when digging the calculated soil, but its main purpose is to fix the bucket relative to the movable section when it is retracted.

All possible combinations of six elements of two can be used in the work cycle. In some cases, it becomes necessary to combine three movements, for example, when planning the bottom of the trench. Any sequence of movements in the work cycle for digging and transport operations can be accepted. Fig. 3 shows a cycle in which there is a combination of three movements when digging and when performing transport operations [17].

When controlling mechanisms in the work cycle, it is desirable that the speeds are not dependent on the load, because operations often must end at the same time. For this, volume control of the speed of movement of the actuators and semi-closed circulation of the flow can be applied.

An example of such a solution is the hydraulic circuit of the UDS-214 excavator. In this hydraulic circuit, some of the mechanisms are powered by a liquid in a closed circulation circuit, and some are separately in an open circulation circuit.



**Figure 3.** Excavator work cycle with backhoe work equipment

1 — operations performed by energy; 2 — short-term operations; 3 — operations performed without energy consumption (the boom lowers under its own weight, the telescope lowers the bucket without soil into the face)

Having data on the flow of pumps, the parameters of hydraulic cylinders and hydraulic motors, as well as assigning the stroke of the hydraulic cylinders and the angles of platform rotation to unload and to the bottom, you can determine the flow rate flowing into the hydraulic mechanisms and out of them during uncombined and combined operations. Using these data it is possible to determine the required make-up for pumps operating in a closed circulation, as well as the flow rates discharged into the tank when there is an excess of flow to the suction of pumps operating in a closed circulation.

The tables below show the parameters of pumps and hydraulic motors obtained from the UDS-214 operating manual. The parameters of the hydraulic cylinders are also given and the costs in the piston and rod cavities, as well as in the cavity of the platform rotation hydraulic motor, are calculated.

**Table 2.** Parameters of pumps and hydraulic motors

Excavator Pumps and Hydromotors					
Designation according to manual		Volumetric displacement	Rotation speed	Volumetric Efficiency	Flow rate
		$V_0$	$n$	$\eta$	$Q$
		$\text{cm}^3$	rpm	%	l/min
416.3.90	1st pump, twin	90	2000	0,9	162
	Make-up pump	19,8	2000	0,9	35,64
416.3.90	2nd pump, twin	90	2000	0,9	162
	Make-up pump	19,8	2000	0,9	35,64
416.3.71	3rd open circuit pump	71	2000	0,9	128
	Make-up pump	19,8	2000	0,9	35,64
406.0.71	Movement hydraulic motor	71	2000	0,9	128
406.0.71	Rotation hydraulic motor	71	2000	0,9	128
406.0.71	Head rotation hydraulic motor, 2 pcs	71	2000	0,9	128

**Table 3.**Parameters of hydraulic cylinders

Pumps, hydraulic cylinders UDS						
	D	d	S	Fp	Fr	$\phi = F_p / F_r$
	mm			m <sup>2</sup>		
Telescope	110	70	4150	0,0095	0,0057	1,66
Boom x2	150	70	1000	0,0177	0,0138	1,28
Bucket	140	70	500	0,0154	0,0115	1,34

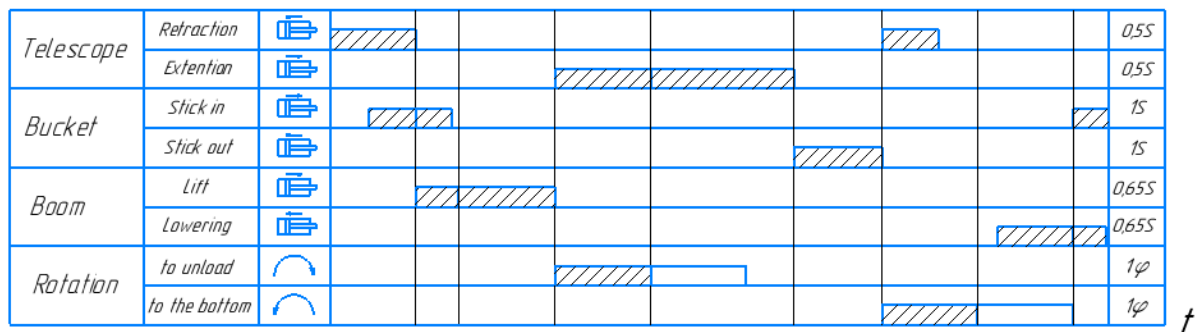
**Table 4.** Flow rates in the piston cavity of hydraulic cylinders

Flow rates in the piston cavity of hydraulic cylinders (excluding efficiency)				
hydraulic cylinders	In the piston cavity	Piston Speed	From the rod cavity	
	Q <sub>pump</sub>	V <sub>p</sub> =Q <sub>pump</sub> /F <sub>p</sub>	Q <sub>r</sub> =V <sub>p</sub> *F <sub>r</sub>	
	l/min	m/s	m <sup>3</sup> /s	l/min
Telescope	162	0,284	0,0016	97
Boom x2	162	0,152	0,002	126
Bucket	128	0,138	0,0016	95,2

**Table 5.** Flow rates in the rod cavity of hydraulic cylinders and the hydraulic motor of the platform rotation during the work cycle

Flow rates in the rod cavity of hydraulic cylinders and the hydraulic motor of the platform rotation (excluding efficiency)						
hydraulic cylinders	In the rod cavity	Piston Speed	From the piston cavity		In the hydraulic motor of rotation	Out of the hydraulic motor of rotation
	Q <sub>pump</sub>	V <sub>p</sub> =Q <sub>pump</sub> /F <sub>r</sub>	Q <sub>p</sub> =V <sub>p</sub> *F <sub>p</sub>			
	l/min	m/s	m <sup>3</sup> /s	l/min	l/min	
Telescope	162	0,474	0,0045	270	128	128
Boom x2	162	0,195	0,0034	207	128	128
Bucket	128	0,185	0,0028	171	128	128

The following is a typical work cycle of an excavator with telescopic equipment for two main operations: during digging and during transport operations. It should also be noted that the work cycle and sequence of actions may be different, and depends on the type of operator control and depending on the operations performed.



**Figure 4.** The sequence of operations of the work cycle indicating possible combinations of working bodies

**Table 6.** Digging suction and discharge flow rates

Delivery to hydromechanisms and discharge and suction flow rates, l / min			
Cycle operations		Digging	
The mechanisms	Direction	telescope, bucket	
Telescope, H1	Retraction	162	
	Extension		
Bucket, H3	Stickin	128	128
	Stickout		
Boom, H2	Lift	162	162
	Lowering		
Rotation, H3	Tounload		
	Tothebottom		
Suction flow rate H1		270	
Suction flow rate H2			126
Drainage flow rate H3		95,2	95,2
$Q_{dis} - Q_{dr}$ for H1		-108	
$Q_{dis} - Q_{dr}$ for H2			+36

**Table 7.** Flow rates of suction and discharge during transport operations

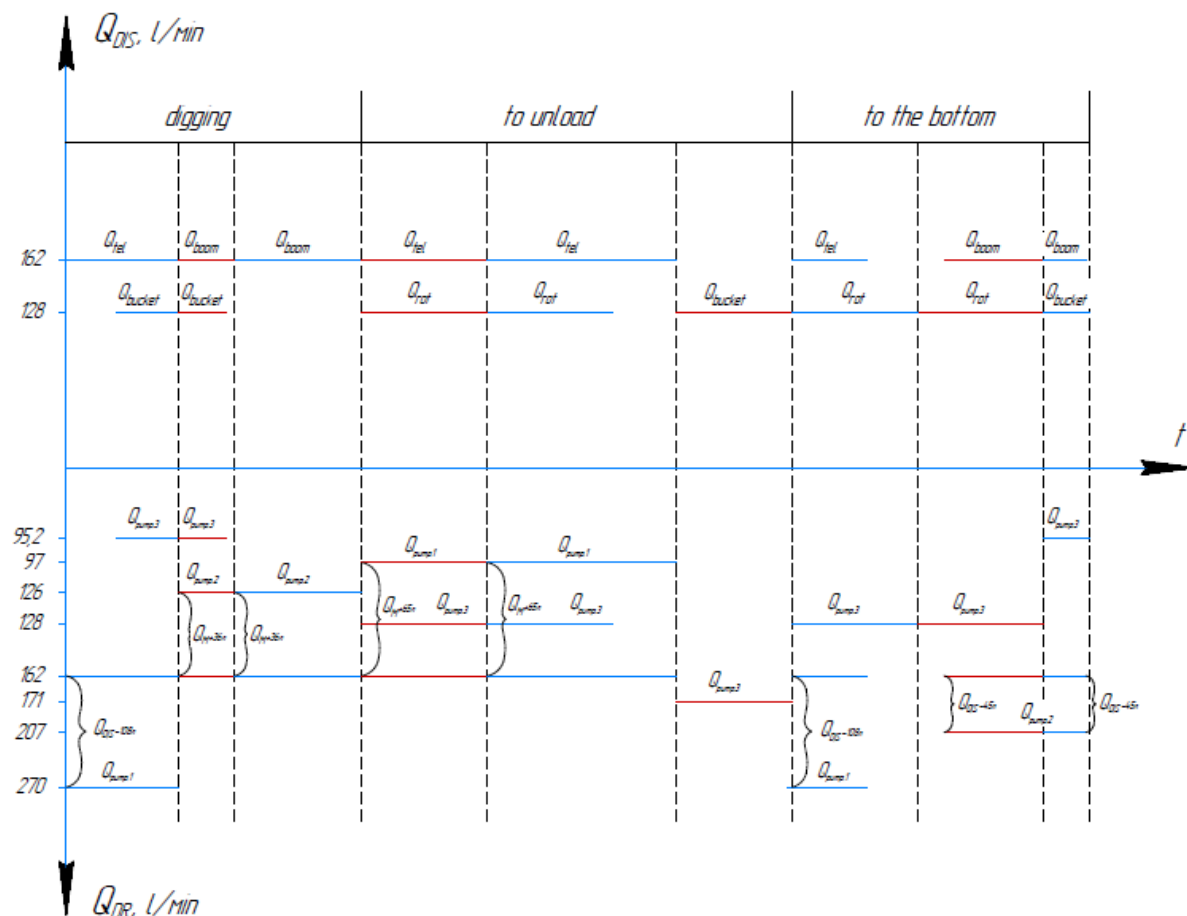
Delivery to hydromechanisms and discharge and suction flow rates, l / min							
Cycle operations		transport operations					
The mechanisms	Direction	Boom, rotation, bucket, telescope					
Telescope, H1	Retraction	162					
	Extension	162	162				
Bucket, H3	Stickin	128					
	Stickout	128					
Boom, H2	Lift						
	Lowering	162 162					
Rotation, H3	Tounload	128	128				
	Tothebottom	128 128					
Suction flow rate H1		97	97	270			
Suction flow rate H2		207 207					
Drainage flow rate H3		128	128	171	128	128	95,2
$Q_{dis} - Q_{dr}$ for H1		+65	+65	-108			
$Q_{dis} - Q_{dr}$ for H2		-45 -45					

The analysis of suction and discharge flow rates in table 6 and 7 shows that when working in the telescoping cylinder rod cavity during digging there is a need to discharge excess flow rate to 108 l/min, and when working in the telescoping cylinder piston cavity during transport operations, need to be fed with a flow rate of 65 l/min. When the boom is lowered, the discharge flow rate is 45 l/min, and when the boom is raised, it is necessary to feed the suction cavity with a flow rate of 36 l/min. These values are determined by the maximum feeds to the actuating hydromechanisms without taking into account volumetric efficiency (volumetric loss coefficient).

Thus, the control valve and, in general, the hydraulic circuit must be able to provide both make-up and discharge of excess fluid for suction. A semi-closed circuit, consisting of two parts, can provide this possibility: the first part is a closed circulation circuit; the second is an open circulation circuit. In addition, a hydraulic device should be provided that provides make-up and discharge of excess liquid for suction.

Below is a diagram of the flow rates entering and leaving the hydraulic mechanisms during combined and not combined movements of the working bodies. Using these data it is possible to determine the required make-up for pumps operating in a closed circulation, as well as the flow rates discharged into the tank when there is an excess of flow to the suction of pumps operating in a closed circulation.





**Figure 5.** Diagram of flow rates in executive hydraulic mechanisms of an excavator planner

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