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AIR EXCHANGE IN QUARRIES

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SUMMARY

The interconnection between the formation of quarry atmosphere contamination with harmful admixtures and a complex of geotechnological and meteorological factors is considered. Conditions and schemes of quarry-space natural ventilation formed in this case are analyzed. The degree of the quarry-atmosphere stability is estimated. Discussed are techniques and means of raising the natural air-exchange rate as well as methods and ways of artificial ventilation of both individual local zones and the quarry space as a whole.

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INTRODUCTION

The application of modern high-duty machines for extraction and transportation of rock mass makes it possible to increase substantially the economically grounded depth of quarries and their space. However, an increase in the space and depth of open mining is accompanied by an increase in the amount of harmful admixtures released to the quarry atmosphere: dust, exhaust gases of dump trucks, soot etc., which leads to an increase of the admixture concentration in the working zone air under conditions of reduced natural ventilation or sometimes in the air of the quarry as a whole. In the latter case the need arises to stop mining.

MAIN PART

Present-day enterprises engaged in open-cut mining of mineral resources are cavities in the earth's crust whose volumes reach tens and hundreds million m^3. The depth of present-day quarries can be as great as 150-450 m, in the nearest future it is planned to carry on open-cut mining at depths up to 700-900 m and above (Table 1).

Table 1. Geometric sizes of quarries

Quarry	Quarry depth, m	Quarry surface sizes, m		Quarry volume, 10^6 m^3
		length	width	
Tulukuy	180	1080	950	97
Pervomaiskii	180	2000	825	156
Kanybay	290	1200	870	158
Muruntau	250	2450	2410	773

The presence of sources of admixtures releasing to the quarry atmosphere and reduction of the natural air-exchange intensity are the main causes of admixture accumulation in air.

As the quarry operation experience has shown, atmosphere contamination of the quarry as a whole or of its individual part is connected, as a rule, with the appearance of atmosphere inversion stratification in the quarry-surrounding territory.

Natural air exchange within the quarry space is formed in response to dynamic (wind) and thermal (thermal stratification) forces which values change with time and space.

The wind condition in the quarry depends first of all on its characteristics in the region under consideration (wind velocity and direction) and geometric sizes (depth, width, length) of the quarry space.

Examples of the daily variation of the wind velocity are shown in Fig.1a. In summer characteristically expressed are day maxima at active manifestation of heat flows.

A change of the wind velocity in the quarry may be characterized by its relative value

$$\Delta U=U_q/U_s \qquad (1)$$

where U_q and U_s are the wind-flow velocities in the quarry and on the surface, respectively, m/s.

A change of the relative wind velocity in the quarry is connected with the presence of heat flows determined by the intensity and distribution of solar radiation. Shown in Fig.1b is the ΔU daily variation in summer and in winter.

In winter as well as with increasing U_s the ΔU change manifests itself less strongly.

Relative-velocity changes in the annual variation are fairly small (see Fig.2), which is indicative of the direct dependence of the wind velocity in the quarry on its value on the surface.

The relative wind velocity decreases with increasing quarry depth, which accordingly reduces the intensity of natural air exchange. Fig.3 presents the profile of the wind velocity in the quarry, which has been obtained from full-scale and model measurements.

For quarry conditions the wind-velocity change at the depth Z from the quarry surface can be expressed with a sufficient accuracy by the expression

$$U_Z= \gamma_1 U_s \frac{\log(H-Z)-\log Z_0}{\log H - \log Z_0} \qquad (2)$$

where U_s is the wind velocity on the surface, m/s; H the quarry depth, m; φ the coefficient taking into account the wind velocity change in movement within the quarry along the X-axis which may be taken to be equal to 0.60-0.67. Characteristic of quarry sections with forward-flow air movement is continued decrease of the velocity from top to bottom according to the dependence described by the power law

$$U_Z=\varphi_1 U_s\left(\frac{H-Z}{H}\right)^m \qquad (3)$$

In this case the exponent m changes over the range 0.3 to 0.6 and is determined by the atmosphere stability, the degree of the surface air flow development within the quarry and the location of the profile considered in one or another section. Characteristic of the backward - flow zone is the velocity change according to the parabolic law

$$U_Z=\left[A(Z-h)^2+B(Z-h)+C\right]U_s \qquad (4)$$

where A,B and C are coefficients characterizing the profile considered; h the depth of the recirculation zone boundary for the section considered, reckoning from the quarry surface.

According to the geometry of the quarry space, under the action of wind there is formed a certain scheme of natural ventilation: forward-flow, recirculation, forward-flow - recirculation and recirculation - forward-flow (Fig.4).

The forward-flow scheme (Fig.4a) is characteristic of shallow quarries, when the angle of slope of the quarry lee flank $\beta \leq 15°$, and is most effective from the viewpoint of natural air exchange. Increased levels of harmful admixtures are only possible here close to sources of the dust-and-gas release.

The recirculation scheme of ventilation occurs at angles of slope of the quarry lee flank $\beta > 15°$. In this case the upper part of the quarry is ventilated by the forward flows coincident with the wind direction on the surface, while the bottom part is ventilated by recirculation flows having the backward direction.

In practice common is a combination of the above schemes depending on the quarry geometry, namely: forward-flow - recirculation and recirculation - forward-flow.

It should be borne in mind that in one and the same quarry at different wind directions and on different stages of mining the scheme of natural ventilation may change.

Thermal forces manifest themselves and act within the quarry space in two forms:
1) temperature nonuniformities of the soil surface layer produced by various sources and forming corresponding air flow directions;
2) atmospheric thermal stratification which characterizes the atmosphere state (degree of stability) and is determined by values of the vertical temperature gradient

$$\gamma = - \frac{\partial t}{\partial z} \qquad (5)$$

Temperature nonuniformities lead to the initiation of convective circulation flows of air. Similar flows are formed from other local sources located in the quarry.

Thermal stratification of the quarry atmosphere is formed by its values in the environment and due to radiation heating or cooling of rocks at the adiabatic compression of the vertical air column.

Thermal gradient values change during a day and according to year seasons. The daily variation shows gradients greater than adiabatic ones chiefly in day time, while values lower than adiabatic ones are connected with night and early morning hours.

In the annual cycle γ values exceeding adiabatic ones are characteristic first of all of summer months due to the presence of an intensive solar radiation inflow. In winter months the repeatability of gradients lower than adiabatic ones increases.

The value of the temperature gradient in the quarry atmosphere can be determined by the equation

$$\gamma = \gamma_a + (\gamma_s - \gamma_a)(1 - e^{P/P_0}) \qquad (6)$$

where γ_a is the vertical temperature gradient in the quarry-surrounding territory, °C/m; γ_s the vertical temperature gradient of the quarry rock surface, °C/m; P the relative quarry depth, $P_0 = 0.43$ is a coefficient;

$$P = \frac{H}{\sqrt{L \times B}} \qquad (7)$$

where H, L, B are the depth, length and width, respectively.

From (6) it follows that at the initial quarry working stage $(P \to 0)$ $\gamma \to \gamma_a$, that is, the temperature gradient in the quarry depends essentially on atmosphere thermal stratification on the surface.

As the relative depth increases, the effect of the geothermal conditions of the quarry as determined by the temperature distribution of the soil surface in the quarry space manifests itself more tangibly. In deep quarries air thermal stratification will depend in many respects on the rock temperature distribution with depth.

If in the quarry there is formed stable stratification $\gamma \leq 0$, which is a consequence of a heat deficit within the quarry space, this leads to the appearance of the air inversion structure which is characterized by the stable atmosphere state with possible accumulation of admixtures, when sources of their release are present. For $\gamma > 0$ the state of air masses in the quarry by and large is unstable.

Acting in combination, the dynamic and thermal components of natural air exchange may be characterized by the thermodynamic-gradient value

$$\gamma_{tg} = \gamma + \gamma_g \qquad (8)$$

where γ is the vertical gradient of the air temperature distribution and γ_g the wind equivalent of the temperature vertical gradient. Its value

$$\gamma_g = \frac{T}{g}\left(\frac{\partial U}{\partial Z}\right)^2 \qquad (9)$$

where T is the air temperature in the layer considered, K; g is the free fall acceleration, m/s^2.

If $\gamma_{tg} > \gamma_A$ ($\gamma_A = 0.01$ °C/m is the value of the adiabatic gradient), the kinetic energy of mixing in the air layer will be sufficient for the formation of intensive air exchange which provides removal and effective dilution of admixtures.

At small changes of the wind velocity with height $\gamma_g \to 0$ and thermal stratification has the main effect on air exchange.

Thus, when passing to work at low levels, a reduction in the air flow velocity and a decrease in the natural air exchange intensity are registered in quarries, which hinders processes of dilution and removal of admixtures released to the quarry atmosphere and calls for additional work on air-exchange control in the quarry, including restriction of the admixture release, dilution and removal beyond the boundaries of the space being ventilated.

Raising the range of natural air exchange is possible by controlling the geometry of the quarry space, structure of wind flows and redistribution of the heat energy as well as by providing artificial ventilation in the quarry.

It has been established that the proposed techniques of raising the rate of natural air exchange in deep quarries ensure different increase of the wind relative velocity. The reliability and efficiency of the technique depend on the geometry of the quarry space, sizes of a device and its placement as well as on the variability of the wind flow direction with respect to the means of raising the air exchange rate.

The greatest increase of the wind relative velocity in the quarry (by 3-4 times) is reached as directing apparatus, an elastic wing and a system of wind-deflecting boards with controllable parameters of a suspension are used (Fig.5). When directing boards are used, air-circulation schemes do not change, but the volume of the recirculation zone in the quarry is reduced.

An elastic wing or a board system make it possible to eliminate completely the zone of backward flows at the quarry bottom. In this case the recirculation zone shifts upwards to the aerodynamic-shadow zone of the wing or board system.

Promoting air exchange in quarries is also possible at the expense of producing directed upgoing air flows in the quarry atmosphere with the use of low-temperature heaters. In this case the air-exchange promotion scheme may be both all-quarrier and local or combined.

Additional heating and heat accumulation are possible, if quarry surfaces are processed with asphalt, bitumen or slag. As this takes place, the colour of rocks changes, which increases the temperature difference between the soil and air in day time by a factor of 2-4. This is connected with increasing absorption capacity of such coatings and accumulation of additional heat quantity in them. The air-exchange rate is raised due to the air flow formed above the processed surface.

To promote natural air exchange, it is also possible to use the depth heat of rocks through which air is pumped (Fig.6). While contacting with deep layers, air is heated and as it again enters the working zone of the quarry, it increases the heat content of the near-ground air layer.

Among other methods of promoting air exchange, it might be well to point out the application of stream ventilation based on the use of turbulent free streams for dilution or for coagulation and precipitation of admixtures with water-and-air streams.

Different scales of using stream ventilation are recommended: from local ventilation of working places to active ventilation of individual zones and even quarries as a whole.

It is common for local ventilation to include ventilation and hydraulic dust removal from individual faces or quarry sections with a high degree of the work concentration.

As means for air-exchange control in the quarry there may be used various mechanical devices producing turbulent free streams as well as heat units forming convective flows. Technical facilities producing free streams are essentially oriented to the use of aircraft facilities (Table 2).

Table 2. Characteristics of quarry ventilators based on aircraft propellers

Ventilator mark	Initial diameter of the stream, m	Initial velocity, m/s	Stream range, m	Drive	
				Type	Power,kW
UMP-1	3.6	22.0	350	Diesel	308
UMP-14	14.6	7.5	570	Electric	320
UMP-21	21.0	9.6	1030	Electric	1000
NK-12KV	5.6	61.0	1300	Gas-turbine	11000
AVK-35	35.0	12.5	1980	Gas-turbine	11000

For local ventilation systems UMP-1, UMP-14, UMP-21 and others have been developed and passed trial testing in quarries.

The sprinkler-and-ventilation system UMP-1 serves for ventilation of local stagnation zones as well as for sprinkling the broken down rock mass and quarry roadbed.

Systems UMP-14 and UMP-21 produce vertical upgoing streams, they are typically arranged at lower quarry levels and promote the removal of harmful admixtures beyond the quarry atmosphere.

The quarry stream ventilator NK-12KV is made on the basis of a TU-114 turboprop engine and is intended for ventilation of and hydraulic dust removal from stagnation zones of a great quarry-space volume.

Ventilator systems based on main rotors serv for ventilation of stagnation zones with upgoing flows.

To produce upgoing convective streams, there are also used heat units:UT-LFI-2, UKPK-1, UPK-1, AVR-70/30 and others. The obligatory condition of the effective use of the heat units is the convective stream leaving the quarry space.

CONCLUSION

Natural air exchange in quarries is determined by the wind energy and thermal forces formed in the near-ground layer at the expense of the solar energy and the earth depth heat.

Disturbances of air exchange accompanied by the accumulation of admixtures are connected with inversions and, as a rule, are observed in windless weather.

Air exchange in quarries can be controlled by promoting natural air exchange and in part by local artificial ventilation.

The control efficiency depends in many respects on routine prediction of possible circulation disturbances.

Present-day requirements limit permissible emissions from the quarry, which puts on the forefront the problems of localization and restriction of the admixture release to the quarry atmosphere.

FIGURE CAPTIONS

Fig.1a. Daily variation of the wind velocity in the quarry and on its surface in January and July.

Fig.1b. Relative wind velocity in the quarry in January and July.

Fig.2. Annual variation of the wind velocity.

Fig.3. Wind-velocity profile in the quarry:
1 - model, 2 - full-scale

Fig.4. Schemes of quarry natural ventilation:
a - forward-flow
b - recirculation
c - forward-flow - recirculation
d - recirculation - forward-flow

Fig.5. Vertical profiles of the wind velocity in the quarry with the use of devices for raising the air-exchange rate:
a - directing apparatus;
b - elastic wing;
c - system of wind-deflecting boards.

Fig.6. Scheme of raising the air-exchange rate in the quarry with the use of rock heat.

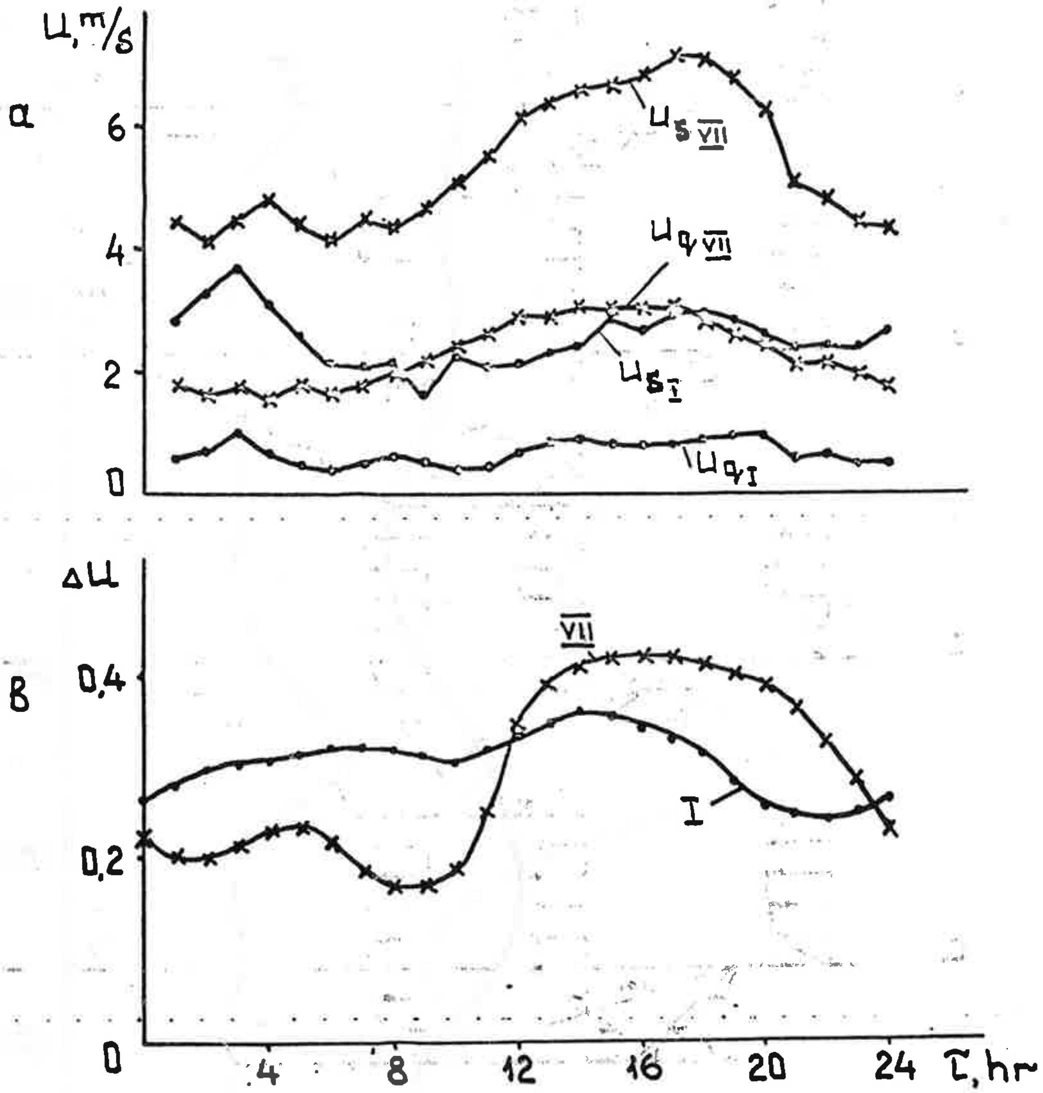

Fig. 1

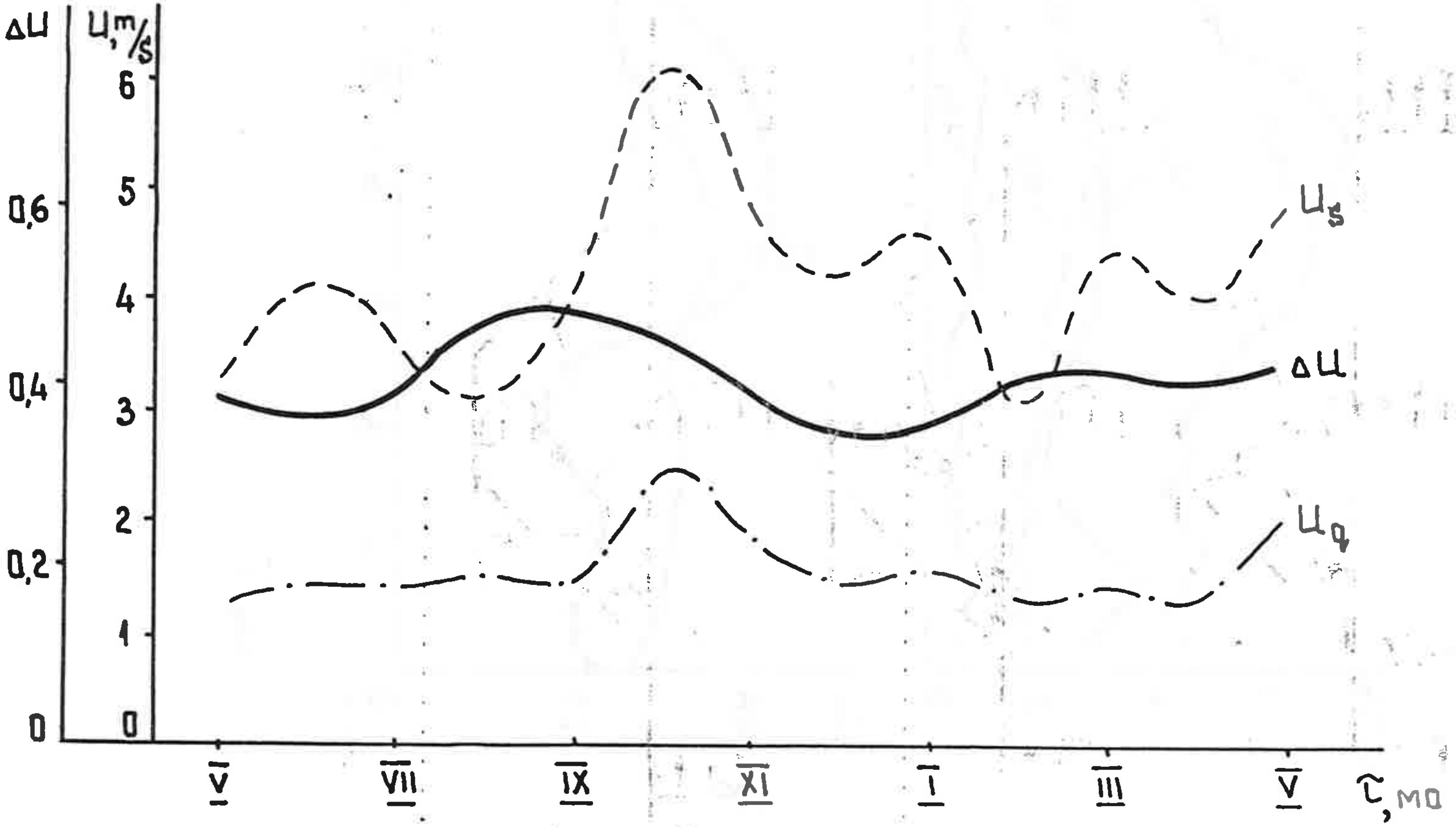

Fig. 2

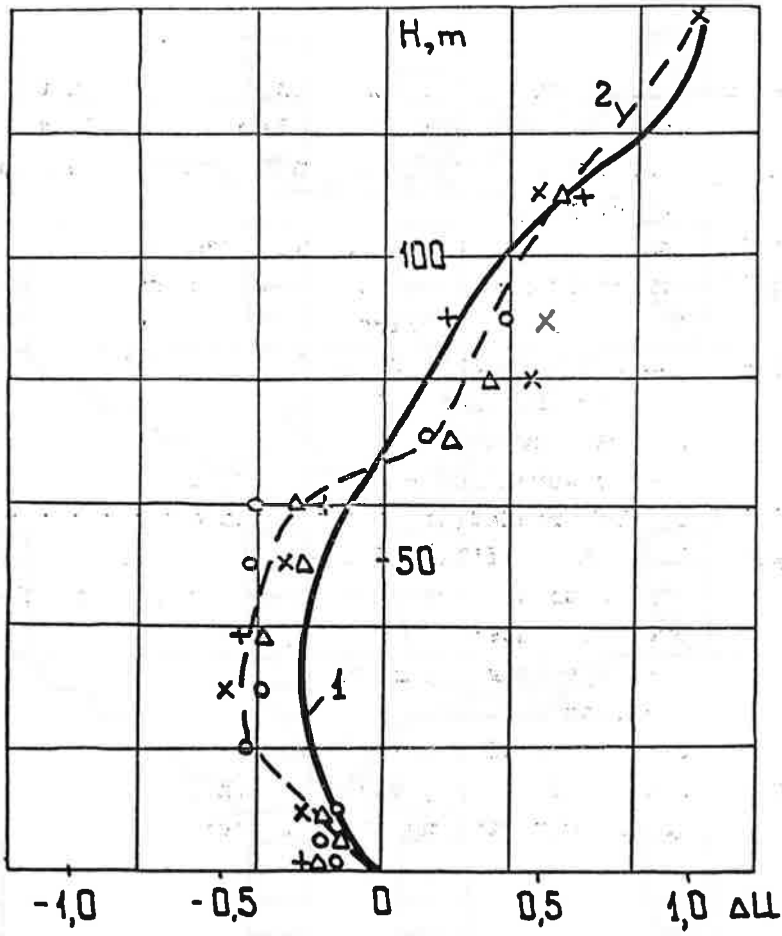

Fig. 3

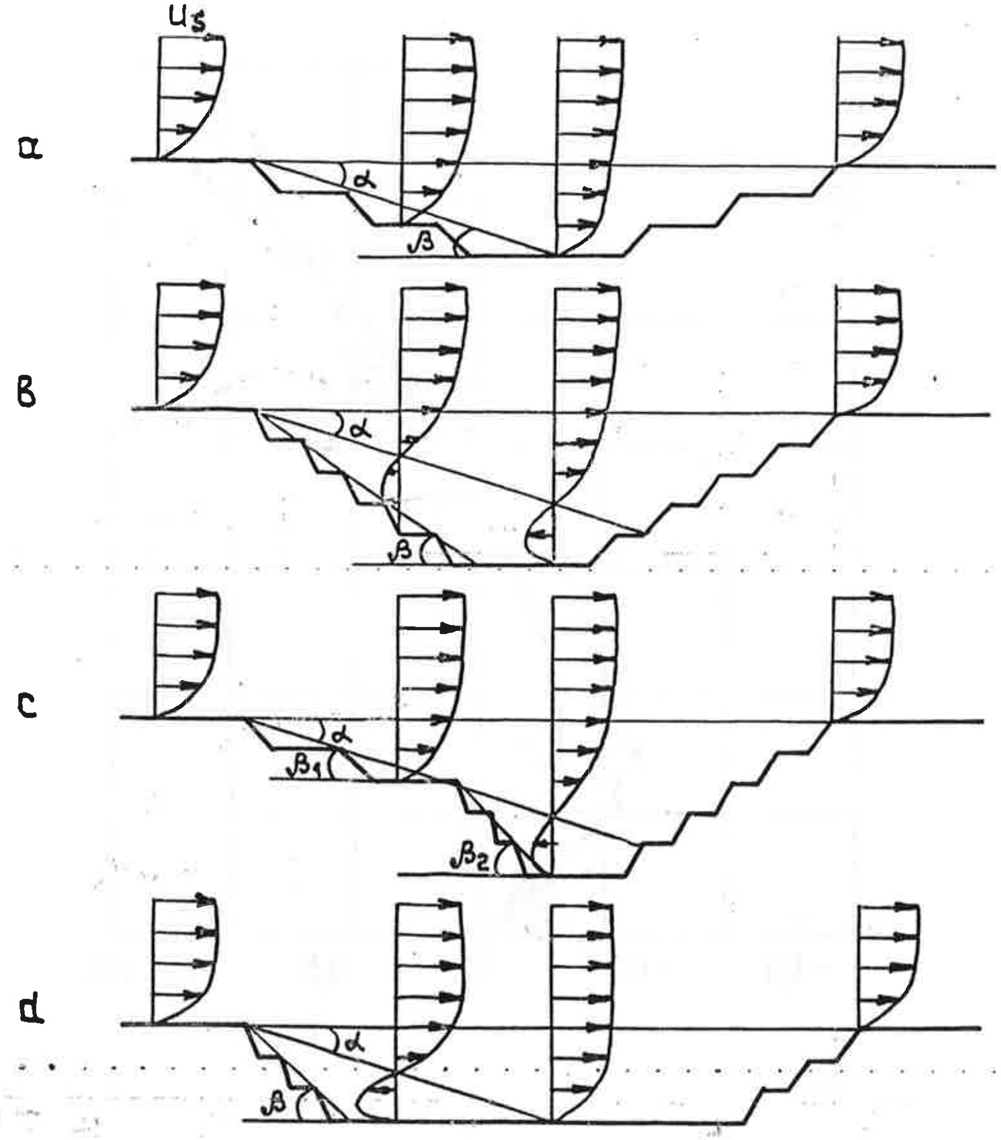

Fig. 4

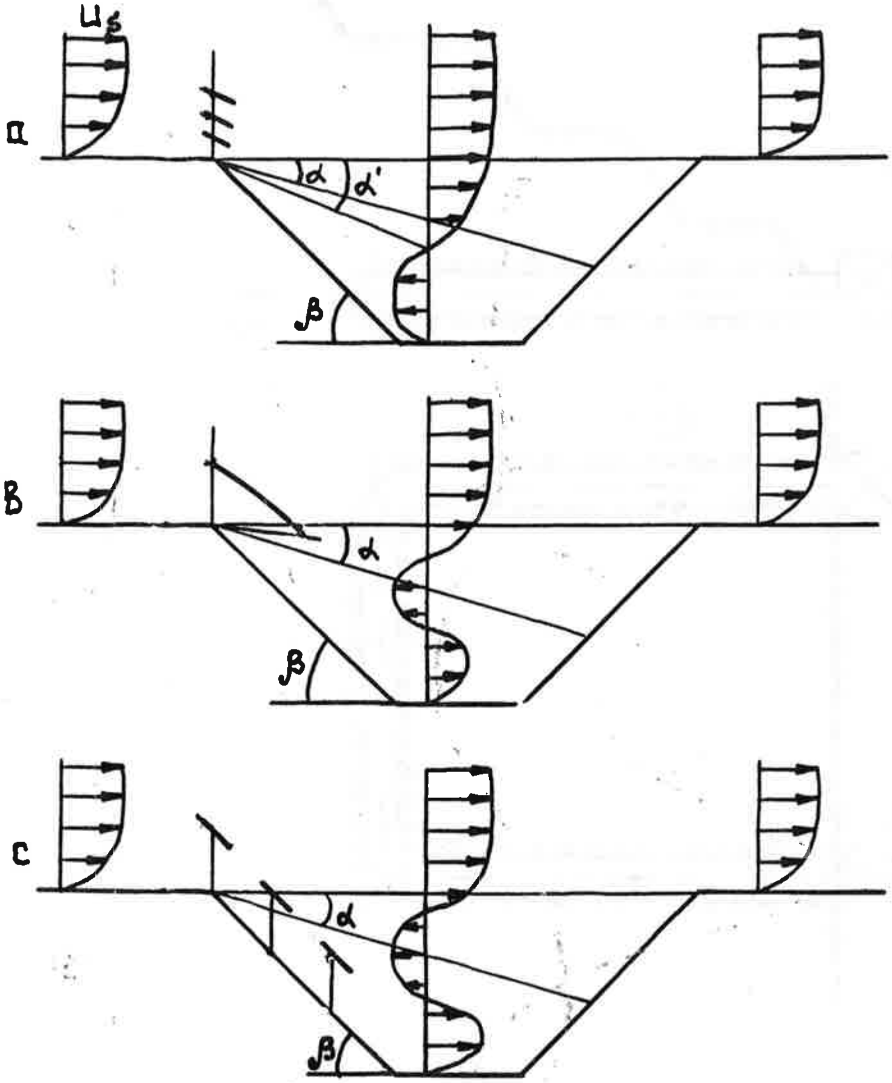

Fig. 5

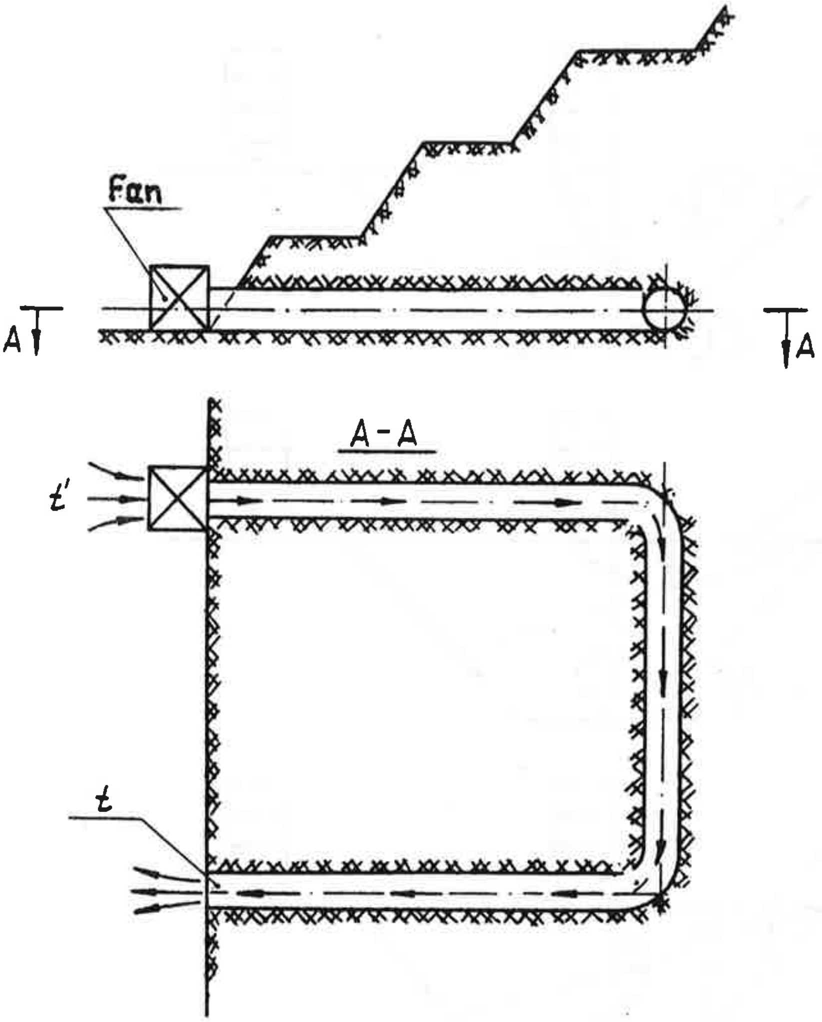

Fig. 6