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# THE EXPERIMENTAL STUDY OF SHALLOW FLOWS OF LIQUID ON THE AIRPORT RUNWAYS AND AUTOMOBILE ROADS

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**Abstract.** Hydroplaning or aquaplaning is associated with the complete loss of the grip of a tyre because of the presence of a water film between the tyres of a moving vehicle (an automobile, an airplane, etc.) and the road surface. In this case, a vehicle becomes uncontrollable. Hydroplaning (aquaplaning) occurs when the speed of a vehicle reaches the critical value, when the wheel does not have time enough for water compulsion, which leads to the formation of a permanent water film between it and the road surface. The higher the depth of the water on the road surface under the tyre, the higher the risk of hydroplaning (aquaplaning). In other words, hydroplaning (aquaplaning) is the floating of the wheel on the water wedge. In physical terms, it is the loss of the ability of a tyre of the effective water compulsion from the contact area with the road. As a result, a water film of several millimeters is formed under the wheel, and a vehicle actually floats up. The article presents the results obtained in the experimental study of the flows of liquid, whose depth is comparable with that of depressions and cambers of rough roadway pavement. It is stated that the relationships used for calculating surface flows should be corrected for shallow flows, taking into account the actual roughness of road covering. Shallow flows are mostly laminar. The transition Reynolds numbers are about 3000. The relationships used for calculating shallow flows may be determined more accurately by test pouring of water on the surface of roadway pavement, with further generalization of the data. The experimental research performed is closely related to the study of the problems of aquaplaning and traffic safety of various means of transport.

**Keywords:** traffic safety, road-holding capacity of a tyre, hydroplaning, aquaplaning, shallow liquid flow, depth of a water film, mode of flow, slope, surface roughness.

## 1. Introduction

It is well known that *hydroplaning* (or *aquaplaning*) is the movement of an object on the surface of water when the object remains on the surface only due to the velocity head of water, i.e. it is gliding or planing over its surface. When hydroplaning begins, the resistance to movement sharply decreases. The effort required to start hydroplaning is much stronger than that needed to remain in this mode. In fact, hydroplaning represents the movement of a body at the point, which is in a highly unbalanced state. In hydroplaning, the supporting force is produced by the dynamic reaction of water, acting on the surface of an object which is in contact with it, while the role of hydroplaning forces is insignificant. The relationship between hydrostatic and hydrodynamic supporting forces depends on the speed of an object.

For example, in transport engineering, when the contact of the vehicle's wheels with the road is described, the term *hydroplaning of the wheels*, which is synonymous to *aquaplaning*, is widely used (for example, the term *hydroplaning* is used when the interaction between airplane wheels and runways is investigated, while *aquaplaning* is used when the interaction between the vehicle wheels and the road is investigated).

Hydroplaning or aquaplaning is associated with the complete loss of the grip of a tyre because of the presence of a water film between the tyres of a moving vehicle (an automobile, an airplane, etc.) and the road surface. In this case, a vehicle becomes uncontrollable. Hydroplaning (aquaplaning) occurs when the speed of a vehicle reaches the critical value, when the wheel does not have time enough for water compulsion, which leads to the formation of a permanent water film between it and the road surface. The higher the depth of the water on the road surface under the tyre, the higher the risk of hydroplaning (aquaplaning).

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In other words, hydroplaning (aquaplaning) is the floating of the wheel on the water wedge. In physical terms, it is the loss of the ability of a tyre of the effective water compulsion from the contact area with the road. As a result, a water film of several millimeters is formed under the wheel, and a vehicle actually floats up.

The term *hydroplaning* originated in aviation, but since the 60-ies, it has become used (as *aquaplaning*) in transport, when the number of high-speed automobiles and the quality of road surface had increased considerably. An airplane taking off from the runway reaches the speed of up to 350 km/h. Such speed was hardly possible for ordinary (not racing) automobiles even in the middle of the 20-th century. Therefore, it is natural that aviators were first to come across the effect of hydroplaning (aquaplaning). When runways became almost ideally smooth and high-speed airplanes were developed, hydroplaning (aquaplaning) became a big problem for aviators. After several crashes of the airplanes which were caused by hydroplaning during the take-off, drastic measures, including the heating of the runway, were taken. At the same time, automobile manufacturers also began to pay attention to this problem.

It is hardly possible to predict the development of hydroplaning (aquaplaning) because there are too many factors influencing this process. The key factors are the state and design of wheel tyres, speed of a vehicle and the quality of the road surface.

A highway, where the speed of vehicles is high and there are many road sections with relatively good asphalt, as well as numerous wheel tracks, is most dangerous.

Water accumulates in them even after light rains, promoting aquaplaning in some cases. The speed value below which a driver may be sure that floating up will not occur does not exist. A heavy truck with modern and narrow rain tyres may easily pass a road section covered with water at the speed of 150 km/h, while an automobile with a rear drive and smooth tyres running at 40 km/h will float up at the same section.

It is hardly possible to predict floating up, but you can easily feel it, and this feeling can hardly be confused with anything else. The steering wheel suddenly becomes 'empty' and the kinetic perception of an automobile is quite different. The worst thing is the floating up of one or two wheels rather than all (which is a rare case). It is clear that the skidding of a vehicle is inevitable in this case.

The problem of hydroplaning (aquaplaning) has been investigated by researchers of various countries for many years now. The speed of a vehicle at which this process may start depends on many various factors, e. g. tread pattern, the degree of the wear of the tyres, quality of pavement, loading of the wheels, depth of a water film, etc.

A survey of papers, dealing with the problem of hydroplaning (aquaplaning) directly or in-directly, is provided below.

The study of pneumatic tyre hydroplaning reported in research by Sinnamon and Tielking (1974) was conducted as part of an ongoing tyre research. A major objective of this study was to collect current knowledge of the hydroplaning phenomenon and squeeze films in the tyre–road contact region. This knowledge is utilized in interpreting the results of experiments conducted with a laboratory apparatus designed to measure the water expulsion effectiveness of a tread pattern. In addition to increase understanding of tread pattern hydrodynamics, a major goal of this work is the development of a set of tread pattern performance parameters which would contain the main aspects of tread pattern geometry relevant to water expulsion effectiveness. Two such descriptors, derived from the experimental and theoretical work reported herein, are proposed. Recommendations for future work to develop additional tread pattern descriptors are discussed.

A decision support system for the safety of airport runways is proposed by Benedetto (2002). The hydroplaning caused serious plane accidents in landing and taking off phases. A decision support system is proposed in order to assess the safety standard during heavy rainstorms. The geometry of the runways and the pavement characteristics are investigated in different hydrological conditions. The application of a decision support system shows that the very short rainstorms (with the duration of about 5 min) are the most critical. The decision support system dynamically computes the depth of the water film through a hydraulic model, which numerically integrates the complete energy and mass differential equations.

The wet-pavement hydroplaning risk and skid resistance were modelled (Ong and Fwa 2007) and analyzed (Fwa and Ong 2008). The theoretical formulation and development of a three-dimensional finite-element model based on solid mechanics and fluid dynamics is also presented in these papers. The hydroplaning speeds computed by the proposed model were analyzed and verified against the well-known experimentally derived NASA hydroplaning-speed equation. The analysis confirmed that the NASA equation is a special case of a general solution, and that it is applicable only to a specific range of tyre footprint aspect ratios. This research presents a numerical simulation of the reduction process of the wet-pavement skid resistance as the sliding speed of a locked wheel increases. The development of the three-dimensional finite-element model used for the simulation is presented. The suggested model is capable of simulating tyre–fluid–pavement interaction of a locked sliding wheel on a wet pavement for hydroplaning and skid resistance analysis.

Fwa *et al.* (2008) presented the analytical modelling of the effects of rib tyres on hydroplaning. This paper describes the analytical simulation study based on the theory of hydrodynamics. The method of modeling using finite element techniques is described. The simulation model is applied to analyze the effect of tyre tread depth on hydroplaning for different surface water depths. The effect of tyre inflation pressure on the hydroplaning risk of rib tyre is also examined. In addition, the effect of different rib tyre designs in relation to the number of grooves is studied.

Ameri and Esfahani (2008) investigated and evaluated the performance of the hydrated lime and limestone powder in porous asphalt. It is known that porous asphalt mixture or open graded friction course (OGFC) has many benefits that resulted in its extensive use and development. OGFC improves the friction of a wet pavement, as well as surface reflection, traffic noise, and wet weather driving conditions by allowing the water to drain through its porous structure, thus reducing the hydroplaning and the splashing and spraying of water in the air (therefore acting as spray reducing surfaces). The goal of this study is the evaluation of the mechanical properties of lime-treated OGFC.

The new methodology was proposed for hydroplaning simulation by using two separate mathematical models (Oh *et al.* 2008). The FDM (finite difference method) code was developed to solve Navier-Stokes and continuity equations and to obtain pressure distribution around a tyre, with the inertial and viscous effects of water taken into account. The FE (finite element) tyre model was used to obtain the deformed shape of the tyre due to the vertical load and pressure distribution. The two models were iteratively used until the converged pressure distribution was obtained. Since the converged pressure distribution could not be obtained near or at the contact zone due to very shallow water, an asymptotic method was also proposed to estimate pressure distribution. This new simulation methodology was applied to a straight-grooved tyre, and its hydroplaning speed was finally determined for the water depth of 5 mm, 10 mm, 15 mm and 20 mm. Moreover, a new simulation methodology using LS-DYNA was proposed, and the two methodologies were compared in terms of accuracy and efficiency.

A realistic analysis of operational landing and stopping performance of large-transport-category airplanes on contaminated runways in adverse conditions is presented by Daidzic and Shrestha (2008). Different landing scenarios were simulated to obtain realistic stopping distances as well as the time histories of deceleration and speed. The model accounts for many contaminated runway scenarios, including hydroplaning, the effect of wind, the speed-dependent rolling-friction coefficient, and other important parameters. Their mathematical model and the simulation program can be used as an operational landing distance calculator.

Reznik and Beljatynskij (Резник, Белятынский 2009) investigated highway design on the sections affected by aquaplaning. They emphasized that the methods ensuring traffic safety on road sections, where vehicle's aquaplaning is possible, should be developed by identifying and improving these sections at the stages of highway design, reconstruction and maintenance and by limiting traffic speed of vehicles.

Ong and Fwa (2009) propose that an important aspect of airport runway geometric design is the ensuring prompt of removal of water from the runway to reduce skidding and hydroplaning risks of airplane operating under wet-weather conditions. Current airport geometric design methods do not explicitly consider the hydroplaning risk, and therefore the adequacy of runway geometric design and the associated drainage system against hydroplaning have not been evaluated. In recognition of the need for a design procedure to ensure safe airplane operation, a framework for runway geometric design taking into account hydroplaning effects was proposed. The proposed framework involves the addition of an independent module for hydroplaning risk calculation to determine whether a trial runway geometric design meets the safety requirement against hydroplaning for the selected design rainfall and airplane traffic. The hydroplaning speed at each point of interest is estimated by using an analytical computer simulation model.

Fwa *et al.* (2009) investigated the effectiveness of tyre-tread patterns in reducing the risk of hydroplaning. Grooving of tyre tread is necessary to provide sufficient skid resistance for wet-weather driving and to reduce the risk of hydroplaning. This paper presents an analytical study that aims to characterize quantitatively the influence of different tyre-tread patterns and groove depths on the hydroplaning behavior of passenger automobiles. The analysis is performed by means of a computer simulation model, based on a three-dimensional finite element approach. The six forms of tyre-tread groove patterns are considered. The analysis shows that a parameter computed as the groove volume per tread area of the tyre is a useful performance indicator to assess the effectiveness of various tyre-tread groove patterns in reducing vehicle hydroplaning risk.

Wang *et al.* (2010) carried out the analysis of the hydroplaning of airplane tyre. Various hydroplaning speeds are investigated, which make a key factor of hydroplaning. The results indicate that hydroplaning speed increases with the increment of inflation pressure, decreasing with the increment of the footprint aspect ratio.

Ong and Fwa (2010) modelled skid resistance of commercial trucks on highways. This research describes the development of a numerical simulation model that can evaluate skid resistance of commercial trucks on wet pavements. The model is developed using the fundamental structural mechanics and fluid dynamics theories with the consideration of tyre–pavement contact and tyre–fluid interaction. The practical significance of the simulation model is illustrated with an analysis of different skid resistance characteristics of trucks when they are unloaded and fully loaded.

The airport runway frictional coefficient is one of the most important factors which affects the safety of airplane's landings and take-offs under various weather conditions, for example, the rain or snow. In this research, each kind of factor which affects the precision of frictional coefficient measurement under the bad conditions such as snow and ice covered, rubber pollution and wet runway has been analyzed, and then the model of frictional coefficient measurement was established (Wang *et al.* 2008).

The performance of four asphalt mixed types was studied under the severe operational conditions in the touch down zone of a high volume runway on a major international airport – Johannesburg (Joubert *et al.* 2004). The asphalt mixes were a medium and a coarse continuously graded mix, an open graded mix and a stone mastic asphalt mix. The performance criteria which included the durability of the mixes to ensure the integrity of the surface were maintained, as well as the surface texture and skid resistance as affected by the rubber build-up on the surface. The study showed that the stone mastic asphalt mix gave the best performance in terms of the overall criteria. The continuously graded mixes had good durability but did not perform as well in terms of retention of skid resistance

Gopalakrishnan (2006) investigates condition, monitoring the airport pavements subjected to the repeated dynamic aircraft loading. In his next research, Gopalakrishnan (2008) presents a simplified approach for predicting the allowable load repetitions for the new large aircraft loading on the airfield runways based on non-destructive test data.

Gopalakrishnan and Khaitan (2010) used Finite element based on adaptive neuro-fuzzy inference technique for parameter identification of multi-layered transportation structures. This research discusses the development of an adaptive-network-based on fuzzy inference system and combined with finite element modeling for the inverse analysis of the multi-layered flexible pavement structures subjected to dynamic loading.

Grooved construction on airport runways has greatly improved the drainage efficiency and skid resistance of pavement. Lee *et al.* (2009) investigated automatic measurement of runway grooving construction for pavement skid evaluation.

Thenoux *et al.* (1996) carried out his study of the aircraft accident related to the asphalt runway skid resistance. The new airplane landed under the good weather conditions on an asphalt surface treatment runway and skidded more than 1000 m. A long investigation provided evidence, why the aircraft skidded off at the end of the runway.

The authors of the present paper experimentally investigated shallow flows of liquid on the airfield's runways and automobile roads. This problem is closely associated with the problems of hydroplaning (aquaplaning) and traffic safety, when various means of transport are used.

## 2. The Significance of the Research

When a runway is covered with a water film, its operational conditions become rather complicated and flight safety may be not properly secured. The surface water decreases the holding capacity of pneumatic tyres. When the take-off or landing speed of an airplane is relatively high (reaching 100–350 km/h), while the pressure in the pneumatics is relatively low, hydroplaning and wheeling out of the plane beyond the rear or side safety belt may take place. As mentioned in ICAO documents (Airport Services Manual 2002), hydroplaning may occur, when a pneumatic runs into a pool with the depth of about 3 mm, and this process continues even when the water film becomes much thinner. In some airports, hydroplaning was observed on the flat smooth runway surface covered by a water film of the depth of only 0.6 mm.

A large amount of water causes spraying as well as increasing the resistance of the airplane wheels to rolling and extending the take-off distance. Getting of water into the engine may be also very dangerous. The holding capacity of tyre is considerably reduced when the water turns into ice, causing an ice-slick.

Most of the road accidents also occur on the slippery road surface, when the road grip of a tyre is decreased (Bogdevičius *et al.* 2004; Nagurnas *et al.* 2007; Sokolovskij 2007a, 2007b; Šliupas 2009; Филиппов *и др*. 2009; Prentkovskis *et al*. 2010). The automobile speed on the roads in Ukraine and Lithuania have already reached 130 km/h (the speed allowed on some highways) and tend to grow further, while the design automobile speed considerably exceeds the officially allowed speed. The decrease of the road grip of a tyre and aquaplaning of an automobile on a highway is a more serious problem than that faced on a runway because the pressure in the automobile tyre is usually about 0.2 MPa, which is considerably lower than the pressure in the airplane pneumatics (ranging from 0.6 to 1.2 MPa).

The analysis of recent research and the literature on the problems of calculating the water flows on the airfield surface (Руководство по проектированию… 1982; Кривенко, Андрущак 1984) shows that the above calculations actually do not take into consideration the shallow flows with depth of 0.25–10.00 mm, comparable with the height of the projections on the road surface. The recommended methods of calculation either refer to turbulent flows of considerable depth or are based on the assumptions of turbulization of laminar flows by the rain drops.

## 3. The Experimental Study

The National Aviation University (Kiev, Ukraine), in cooperation with Vilnius Gediminas Technical University (Lithuania), has been carrying out the research aimed at developing the automatic system of distant control and prediction of the runway state (Кривенко 2002). In the framework of this research, a sensor of the water film depth on the take-off/landing runway has been suggested. To assess the state of the whole surface based on the readings of the sensors, fixed at certain points of the pavement, and for determining these points, the experimental study of the water flows with the depth of 0.2–20.00 mm was performed.

To carry out the experiments, two laboratory-scale plants, one for working in the laboratory and another intended for work in the outdoor conditions, were created. In addition, the research was carried out on the take-off/landing runways.

The laboratory plant (Fig. 1) is 3.7 m-long double tee steel on which 40 mm-thick layer of concrete is placed and compacted by a vibrator. The surface was smoothed and floated with Cement 400. Floating with cement is a method of protecting the surface of concrete structures from water penetration, allowing for smoothing their surface as well as increasing strength and durability. The slope of the shoot can be changed from 0°

to 0.02° and the readings are shown by indicator 4. The water is supplied to the shoot by a water pipe-line or by a pump if the consumption is over 150–200 $cm^3$/sec. The depth of the flow was measured by measuring needles on three section-lines shown in Fig. 1. The section-lines were chosen so that the influence of the inlet and outlet sections could be eliminated. The stability of the flow depth and consumption was controlled by the flow depth sensor 11 and register 12.

To check the effect of the rain drops on a transit flow, a sprinkler system, consisting of a pipe-line of 20 mm in diameter and having the opening with the fixed nibs for forming drops and ensuring their uniform distribution over the flow surface was used.

The plant aimed at working in the outdoor conditions differs from the laboratory plant only in size (the width of the flow is 370 mm, while its length is 8 m) and it does not have a sprinkler system and a pump. The surface of the shoot of this plant is much rougher due to the exposure of concrete to rain, show and low temperatures (for more than three years).

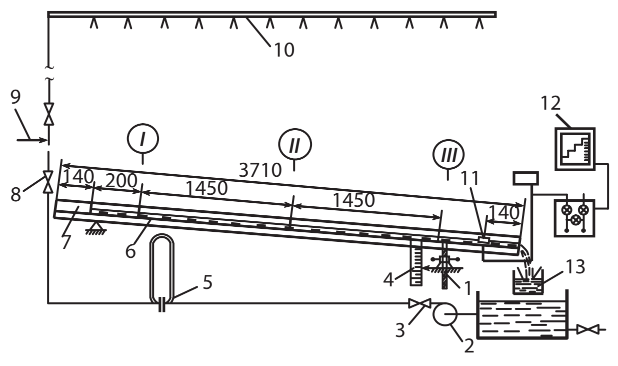


**Fig. 1.** A schematic view of the laboratory plant with a shoot of 280 mm width: 1 – a hoist; 2 – a pump for the follows deeper than 5–6 mm; 3, 8 – a gate valve and valves for regulating water consumption; 4 – shoot slope indicator; 5 – water meter; 6 – a double tee; 7 – a damper; 9 – water supply by a water pipe-line; 10 – a sprinkler system; 11 – the water flow depth sensor; 12 – a register; 13 – a vessel for measuring water consumption

The roughness of the surface was measured following the ICAO recommendations (Airport Services Manual 2002), i. e. by covering it with sand and lubricating material. Then the measured sand or lubricant was smoothed and the mark (print) was measured. The roughness of the concrete surface of the shoot in the laboratory was about 0.1 mm, while, under the outdoor conditions, it reached about 0.4 mm.

At the considered stage of research, a transit flow was investigated, implying that the effect of the rain drops was not taken into account. It should be noted that such flows are most often observed on the runway. The runway was 40–50 m wide, while a transit flow was formed at the start of the slope. The effect of the rain drops is likely to be strong at the first slope section, which will be an important factor for short slopes, which are most common for automobile roads. The authors hope to study the considered effect in the future.

The results of the laboratory experiments are presented in Fig. 2 as the relationships between the flow depth $h$ and the consumption $Q$, and in Fig. 3 as the relationships between the resistance $\lambda$ and Reynolds number ($Re$).

The choice of the resistance coefficient $\lambda$ was considered by the authors to be more suitable for processing the data because it is commonly used for pressure flows instead of Sheetz coefficient, which is usually used for gravity or river bed flows.

The coefficient $\lambda$ was found by applying the Darcy formula aimed at calculating a flat flow:

$$\lambda = 8 \cdot g \cdot h \cdot i / V^2, \quad (1)$$

where: $i$ is the slope; $V$ is the average speed of the flow ($V = Q/(h \cdot b)$, where: $Q = W/t$; $b$ is the width of the flow; $W$ is measuring vessel capacity; $t$ is the time of filling the vessel).

In the laboratory experiments, a measuring vessel was placed at the end of the shoot, while in the outdoor (runway) experiments, it was placed under the pipe-line leading from the water tank at the initial shoot section.

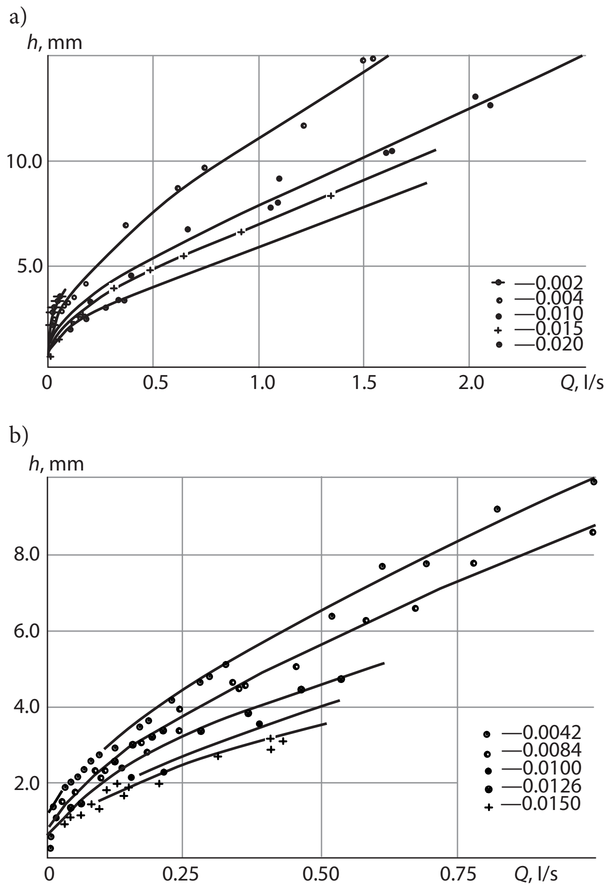


**Fig. 2.** The dependences of the flow depth $h$ on the consumption $Q$ on the concrete surface: a – roughness $\Delta$ = 0.1 mm; b – roughness $\Delta$ = 0.4 mm of the surface exposed to atmospheric action for a long time (the bed slope of the flow is points)

The Reynolds number was expressed as:

$$Re = 4 \cdot V \cdot h/\nu, \qquad (2)$$

where: ν is kinematic viscosity.

The analyses of the results obtained, as well as the evaluation of errors made in measuring the particular parameters in the course of experimenting, allow us to consider that the experiments are true. Accurate measuring of the flow depth posed the main problem. The accuracy of measuring by measuring needle is 0.05 mm (which makes a half of the scale graduation value of the device). However, taking into account the roughness of the surface, the placing of the device (a measuring needle) should be paid special attention. The places of fixing the device on the laboratory shoot were constant with respect to its length and width of the section-line. First, the flow depths about 3–4 mm were measured in the lateral section-line, with the shoot located in a horizontal position. This allowed us to determine the lateral section (profile) to the accuracy of 0.1 mm. then, the average depth mark was determined and the needle of the device was placed over it. The readings from the device scale were taken when the needle touched its reflection in the water. The readings were usually taken by two observers. It is clear that lengthwise shoot surface roughness affected the shallow flows by distorting the particular streams to some extents. The distortion actually depended on the water flow rate. The accuracy of the obtained data is shown by the data presented in the paper.

Based on the results obtained in the laboratory by experimenting with a smooth surface (Δ ~ 0.1 mm), the following dependences may be recommended for calculating shallow flow depth and rate:

– ***for laminar flow*** (when $Re = 4 \cdot V \cdot h/\nu < 3000$):

$$\lambda = 167/Re. \qquad (3)$$

The line 2 in Fig. 3a corresponds to the above dependence (3).

For ordinary flows $\lambda = 96/Re$ (see line 1 in Fig. 3a).

– ***for turbulent flow*** (when $Re = 4 \cdot V \cdot h/\nu > 3000$):

$$\lambda = 0.11 \cdot (\Delta / 4 \cdot h)^{0.25}. \qquad (4)$$

The line 3 in Fig. 3a corresponds to dependence (4), which is a well-known Shifrinson formula, expressed as follows for pressure flows:

– for pipe-lines of circular cross-section with the diameter $D$:

$$\lambda = 0.11 \cdot (\Delta_e / D)^{0.25}; \qquad (5)$$

– for pipe-lines of an arbitrary shape with a hydraulic radius $R = \omega/\chi$:

$$\lambda = 0.11 \cdot (\Delta_e / 4R)^{0.25}. \qquad (6)$$

In formulas (5) and (6), $\Delta_e$ the equivalent pipe-line roughness is given; $\omega$ is a free cross-sectional area; $\chi$ is a wetted perimeter. For enforced flows, $D = 4 \cdot R$, while for smooth (flat) flows $R = h$ are commonly used.

The agreement between flat shallow flows (with the depth of about 5–20 mm) and ordinary flows under the conditions of turbulence, observed in the experiments performed, may be considered to be a complimentary proof of the validity of a considerable increase of the numerical coefficient by more than 1.7 times (167/96 = 1.73) in the well-known formula (3) for flat free flows, which was obtained in these experiments.

The data of measurements made on the real runways were affected by the specific conditions of their use, often preventing us from repeating the required measurements.

Special attention was paid to experimenting with the shoot, having the surface exposed to rain, snow and frost for a long time. The shoot surface turned out to be insufficiently strong to withstand such actions. However, the shoots with similar surfaces are not rare, therefore, the present experiments may be valuable for such cases. In the future, the authors intend to carry out the experiments with real rainfalls, using the shoot of the described type.

A positive effect on measurement of the water film depth (Кривенко, Андрущак 1984) by the automatic sensor, connected to the recorder, should be emphasized. The sensor was certified by the state metrological service, which stated that the main error of the device for

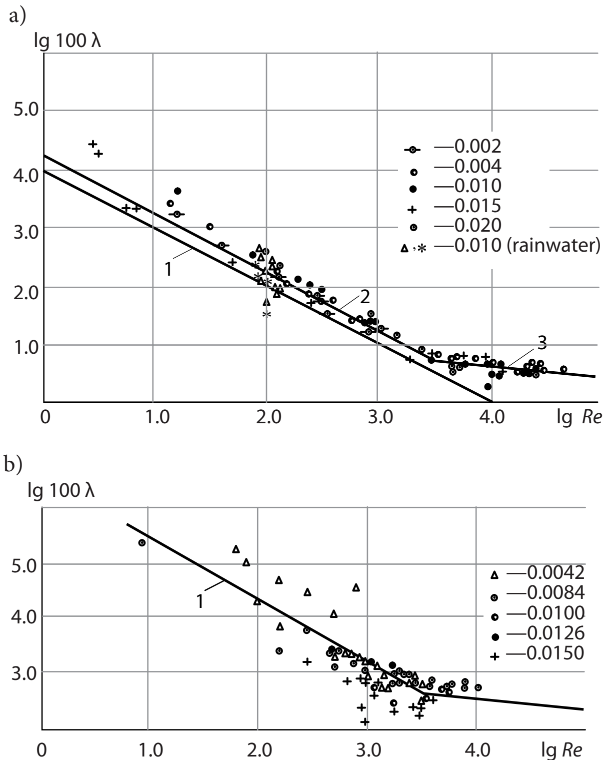


**Fig. 3.** The dependences of the resistance coefficients λ on the flow mode (Reynolds numbers) for shallow flows on concrete surface: a – surface roughness Δ = 0.1 mm; 1 is a line corresponding to ordinary smooth flows (λ= 96/*Re*); b – is surface roughness Δ = 0.4 mm (the surface was exposed to atmospheric action for a long time), 1 is the line corresponding to the surface with Δ = 0.1 mm given in Fig. 3a

water column of 0.4 mm ranged from 0.1 to 10.0 mm. Recording the film depth during a certain period of time allowed the authors to control the performance of the experiment.

The roughness of the runway section surface, where the experiments were made (Zhuliany International Airport, Kiev, Ukraine), reached 0.44 mm. The experiments (Fig. 4) were performed before the reconstruction of the runway was made (2009), therefore, the influence of the expansion joints of the slabs could be observed. It should be noted that the slabs (3 × 4 m) were placed after the Second World War and the expansion joints were not always filled appropriately, i. e. flush with the concrete surface. A shoot on the runway was 1 m wide and 12–20 m long, while the surface roughness of the shoot was about 0.44 mm.

The concrete surface in the Mineralnye Vody Airport (Russia) was in a much better state. The slabs, measuring 7.5 × 15 m, were placed much later, and their expansion joints had practically no influence on the flow of water. The shoot was 1 m wide and 19–25 m long. The runway also had special furrows, 2–3 mm deep, which were made after placing the concrete. They were used to increase the effectiveness of water removal and the road grip of pneumatics. The furrows were perpendicular to the runway axis, usually matching the slope and direction of the flow of water. These runway's peculiarities largely contributed to a considerable reduction of the coefficient λ.

At the last stage, the qualitative analysis of the effect of the rain drops on the transit flow of water was made, using the laboratory stand, shown in Fig. 1. The results of the experiments are presented in Fig. 5. As can be observed, the rain drops had caused turbulization of the main flow, which remained laminar. However, in the experiment, the consumption made about a third of the transit flow due to rain.

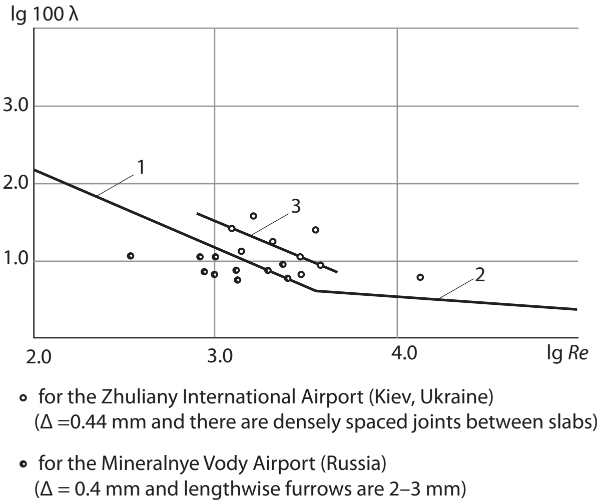


**Fig 5.** The dependences of the resistance coefficients λ for shallow flows on concrete surface on the flow mode (Reynolds numbers): 1 – the line corresponding to the line 2 in Fig. 2a which refers to the laminar flow on a relatively smooth surface; 2 – the line, corresponding to a turbular flow on a relatively smooth surface; 3 – a laminar flow for the surface of an old runway in the Zhuliany International Airport (Kiev, Ukraine) with the slabs (3 × 4 m), having low quality joints (λ= 344/*Re*)

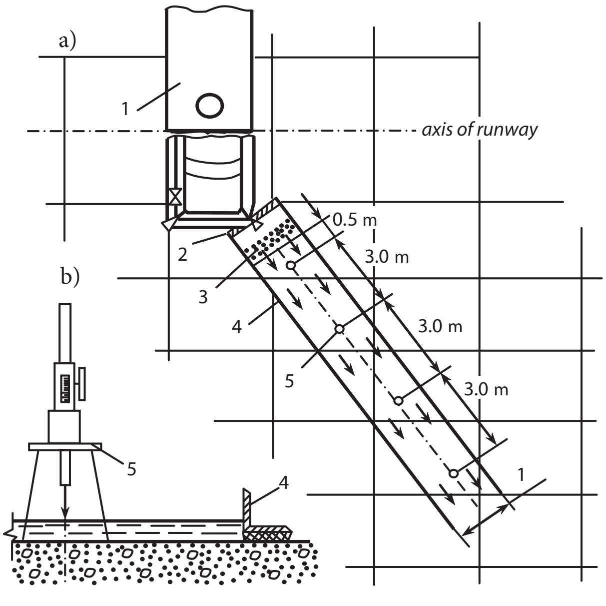


**Fig. 4.** A schematic view of the experiment carried out on Zhuliany International Airport (Kiev, Ukraine) runway: a – the location of the sprinkling machine (1 and the shoot 4; 2 is a watertight partition; 3 is a damper (a gravel layer); 5 denotes the points of measuring water depth by a measuring needle); b – the scheme of fixing measuring needles in the shoot

As mentioned above, taking into account considerable lengths of the flow on the runway, transit flow should be paid more attention. The stronger effect of the rain drops may be expected on automobile roads because their width is much smaller. The higher influence of the automobile wheels and wheel-tracks on water flow may be expected on automobile roads, where traffic is much heavier than in the airfields. The authors are going to perform a more detailed study in this area.

## 4. Conclusions

The experiment study of shallow flows of liquid allowed the authors to reveal and quantitatively evaluate a considerable effect of the surface roughness on the design relationships (which, as far as they know, has not been done before) and to suggest a new coefficient to be introduced into a well-known formula for calculating flat laminar flows of water. This coefficient turned out to be 1.7 times higher than that, which is commonly used for relatively flat and smooth surfaces.

A hypothesis is made that the increase of the coefficient is caused by considerable bending of the streams of liquid and the variation of their speed under the influence of rough surface and power loss due to the interaction of the streams.

It has been found that strong effect of surface roughness still does not lead to flow turbulization. The critical Reynolds numbers are considerably larger for shallow flows than those obtained for common and enforced flows of liquid.

The rain drops did not cause flow turbulization in the experiments performed.

It has also been found that, in turbulent shallow flows, the resistance does not increase, which may be accounted for by a considerable increase of the kinetic energy of the streams and the sufficient increase of the depth of turbulent flows under the experimental conditions.

The following conclusions may be made:

1. The water on the runway and on the automobile road surface largely decreases the holding capacity of the wheels of a vehicle (an airplane, an automobile, etc.), which may cause hydroplaning (aquaplaning). A threat of the water to traffic safety increases due to a continuous growth of the vehicle speed and actually stable pressure in automobile pneumatics, which is about 0.2 MPa (to reduce a threat of hydroplaning on the runway, the pressure in airplane pneumatics, reaching now 1.0–1.3 MPa, is being constantly increased, while to decrease the jolting in the airplanes, powerful shock-absorber struts of the airplane wheels are being improved).
2. In designing and maintaining runways and automobile roads, the presence of water on their surfaces and its effect on traffic safety should be taken into account. The experimental study, considering a wide range of problems, has shown that the relationships commonly used in airfield and automobile road design for determining the depth of the water film on their surfaces are valid only for turbulent flows. However, laminar flows are often found in practice, whose depths considerably exceed the design ones.
3. Experimentally obtained more precise relationships may be used for preliminary evaluation of the effect of precipitation on the depth of the water film on the pavement surface. Since it has been found that the water film depth largely depends on the roughness of the surface, the coefficients used in design calculations may be corrected by test sprinkling of actual pavement surfaces in any particular case.

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