TRANSPORT PROBLEMS 2019 Volume 14 Issue 1
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2019.14.1.2

**Keywords:** tire; slush layer; sub-block; friction force

**Marijonas BOGDEVIČIUS*, Andrius RUŽINSKAS, Vaidas VADLŪGA, Paulius BOGDEVIČIUS**
Vilnius Gediminas Technical University, Faculty of Transport Engineering
Saulėtekio av. 11, Vilnius, 10223, Lithuania
**Rimantas KAČIANAUSKAS, Algirdas MAKNICKAS**
Vilnius Gediminas Technical University, Faculty of Mechanical Engineering
Saulėtekio av. 11, Vilnius, 10223, Lithuania
**Frank GAUTERIN**
Karlsruhe Institute of Technology, Institute of Vehicle System Technology
Rintheimer Querallee 2, 76131 Karlsruhe, Germany
**Corresponding author*. E-mail: marijonas.bogdevicius@vgtu.lt

# INVESTIGATION OF TIRE FORCE TRANSMISSION ON INTERACTION WITH SLUSH

**Summary.** The main parameters describing the interaction between a tire and the road are forces transmitted by a tire. This paper presents experimental and theoretical research of mechanism of force transmission between a tire and slush-covered pavement. The experimental research was conducted in the internal drum test facility at the Karlsruhe Institute of Technology in Germany. The theoretical research presents a mathematical model of the system “"sub-block–slush layer–drum” focusing on slush behavior. The model evaluates mass change velocity of slush layer, mass, and physical–mechanical properties of sub-block. Slush was analyzed as a multi-layer bulk. The obtained velocities of slush layers and friction forces from the model allowed us to determine the generated heat per time unit at each layer. It was found that the top layer of slush has the highest velocity and heat flow values compared to other layers.

## 1. INTRODUCTION

In regions with extreme winters such as Scandinavian and Baltic regions, road safety during winter season is a matter of utmost concern for transportation officials. Driving conditions in winter can deteriorate and vary dramatically because of snowfall and ice formation, causing a significant reduction in tire friction and increasing the risk of accidents [1-4].

In order to ensure traffic safety, the controllability of a vehicle in all seasons and weather conditions is of special importance. When tires come in a direct contact with the pavement, a grip is formed, which directly controls a vehicle; parameters of tires have a great influence on the control, stability, and safety of the vehicle [5].

To engineer tires in a better way to be used efficiently in winters, the factors influencing the friction and the contact mechanics should be well studied. Besides the behavior of rubber material, the friction mechanisms of rubber are very complex as well. The viscoelastic material properties of rubber cause a complicate friction behavior, which depends on the contact area, the sliding velocity, the normal pressure, and the ambient temperature. The rubber friction, in general, is dominated by four single mechanisms [6, 7]:

- Hysteresis – caused by internal damping of the rubber material.

- Adhesion – described as an increase in physical bonding between two bodies, when they are brought in a close contact.
- Viscous friction – occurs in lubricated contacts.
- Cohesion – the generation of wear particles or cracks on the rubber surface.

The total friction force is assumed to be the sum of these components.

Experimental tire testing can be classified into laboratory and road measurements. Testing tires outdoor on winter tracks such as snow, ice or slush is very challenging, as track and ambient parameters continuously change. Indoor testing allows us to control these parameters; hence, measurements become much more reproducible than outdoor measurements. As a tire is a very complexly engineered object, to reduce the difficulty and complexity of the tire testing, it can be practicable to test only parts of a tire. For example, the study of the interaction between tire tread and road surface can be done with a single tread block. It allows investigating the dominating friction mechanisms [8].

There are studies on the mechanism of force transmission of tire in snow or ice [9-12] and the friction mechanism between tire tread blocks and ice or snow-covered pavement [13-15], but there is a lack of studies analyzing the interaction between a tire and slush. The closest investigation is presented by Lee and Huang [16]. The authors have used the wet snow definition described by the International Snow Classification [17] and presented the outdoor measurements using a special test vehicle. Meanwhile, this paper studies the interaction between a tire and slush, which, according to the International Snow Classification, is described as soaked snow with water and its volume fraction is higher than 15%.

## 2. EXPERIMENTAL AND THEORETICAL INVESTIGATION

### 2.1. Methodology of experimental research

The measurement of tire force transmission was conducted using the internal drum test bench at the Karlsruhe Institute of Technology in Germany. The test facility provided the opportunity to perform measurements on different track surfaces and under various operating conditions. It consisted of the drum with a diameter of 3.8 m, wherein a tire, mounted on a facility wheel suspension, rolled on the installed track (Fig. 1). Wheel and drum could be tested independently for braking and traction evaluation. Sideslip and camber angles and vertical load were adjusted by the hydraulic system. The test facility was surrounded by a climate-controlling chamber with an air-conditioning system that cooled down the testing room to –20 °C.

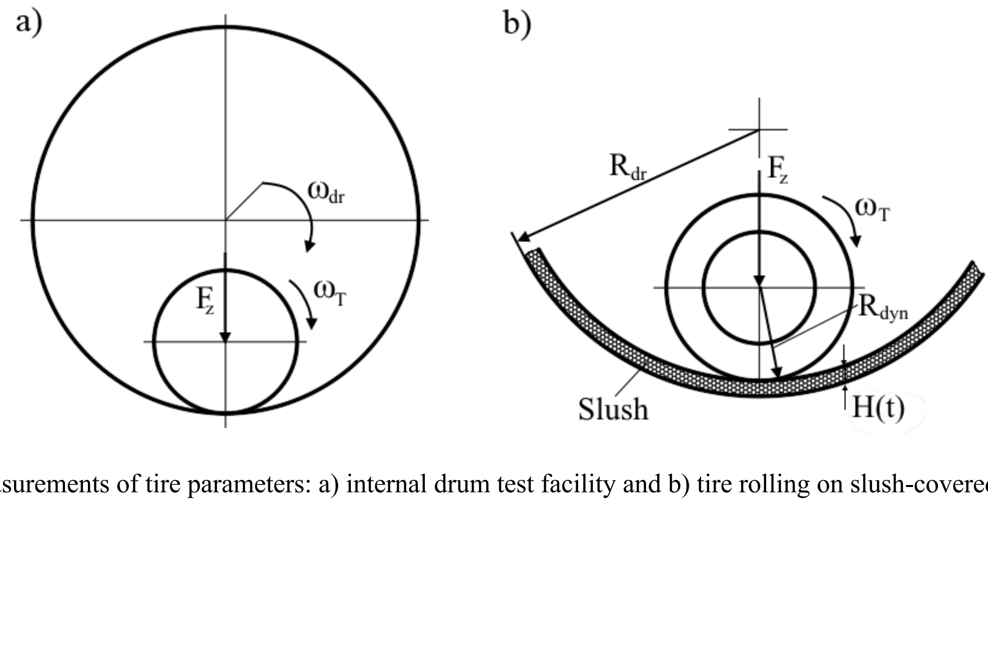


Fig. 1. Measurements of tire parameters: a) internal drum test facility and b) tire rolling on slush-covered drum

Tire–slush measurements were performed with the initial height of slush layer being 4 cm. It was obtained by mixing 110 l water with 22 l of fresh snow. The mixture was rotated in the rotating drum at about 55 km/h to spread it equally on the drum surface. Then, one tire acceleration measurement was conducted, which took about 14 s. The main parameters of interaction were measured: wheel load ($F_z$), longitudinal friction force ($F_x$), tire angular velocity ($\omega_T$), drum angular velocity ($\omega_{dr}$), dynamic radius of the wheel ($R_{dyn}$), and slip ($S_x$). A special 205/55 R16 winter tire was used, and its tread pattern is shown in Fig. 2a. The tread height was 8 mm.

### 2.2. Theoretical analysis of tire–slush interaction

The tire–slush interaction measurements were conducted at the macro-level and main parameters ($F_z$, $F_x$, $S_x$, etc.) were obtained. For the evaluation of contact parameters between tire and slush, it was assumed to conduct measurements at the micro-level, focusing on the mathematical evaluation of slush and its behavior. For this reason, an interaction between sub-block and slush layer (Fig. 2b) was analyzed. The sub-block is a part of tread block separated with sipes (Fig. 2b). A tread block usually has four or five sub-blocks that are in direct contact with the road surface.

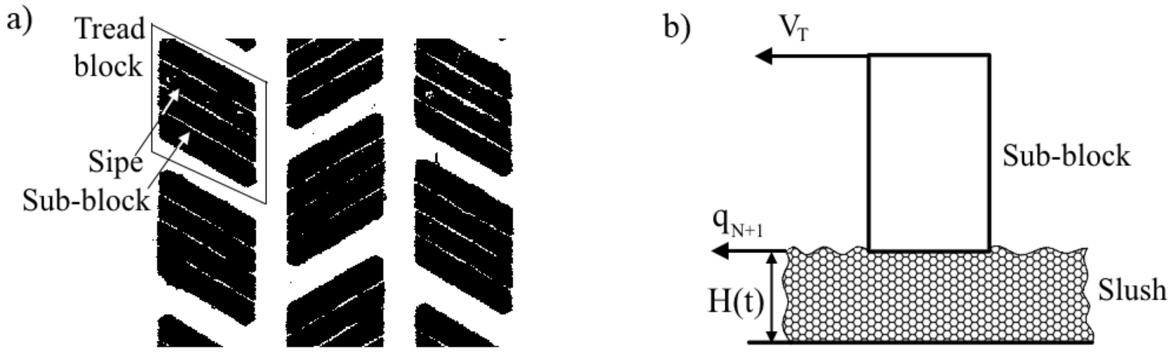


Fig. 2. Concept of tire–slush interaction: a) tire tread parts and b) sub-block interaction with a slush layer

To evaluate the friction between the sub-block and top layer of slush, the velocities of sub-block and top slush layer should be known. When slush is moved in a drum, both bottom and top slush layers move and their velocities are different. The movement of the slush layers depends on its dynamic viscosity. Slush dynamic viscosity depends on multi-component bulk (snow crystals, water, and air). Slush, as the multi-component bulk, is compressible; therefore, its dynamic viscosity depends on bulk compressibility.

In the presented theoretical model (Fig. 3), the mass change velocity is evaluated.

The interaction between sub-block and slush layer also depends on the physical–mechanical properties of sub-block material and geometric parameters (height, width, and length). The physical–mechanical properties were evaluated through stiffness ($k_e$) and damping ($c_e$) coefficients. The mass of sub-block was also evaluated in the model.

Dynamic viscosity of slush is calculated as follows:

$$\mu_{Sl} = \mu_{Sl,0} + a_{Sl} I_{Sl}^{b_{Sl}} \quad , \tag{1}$$

where $\mu_{Sl,0}$ is the initial dynamic viscosity, and $a_{Sl}$ and $b_{Sl}$ are the coefficients.

Inertial number $I_{Sl}$ is defined by [18]

$$I_{Sl} = \frac{dv}{dh}\sqrt{\frac{m_{Sl}}{p_0}} \quad , \tag{2}$$

where $p_0$ is pressure ($p_0 = 10^5$ Pa), $v$ is the velocity of slush, $h$ is the slush height, and $m_{Sl}$ is the mass of slush, calculated as follows:

$$m_{Sl} = \rho_{Sl} \cdot V_{Sl} \quad , \tag{3}$$

where $\rho_{Sl}$ is the density of slush and $V_{Sl}$ is the volume of slush.

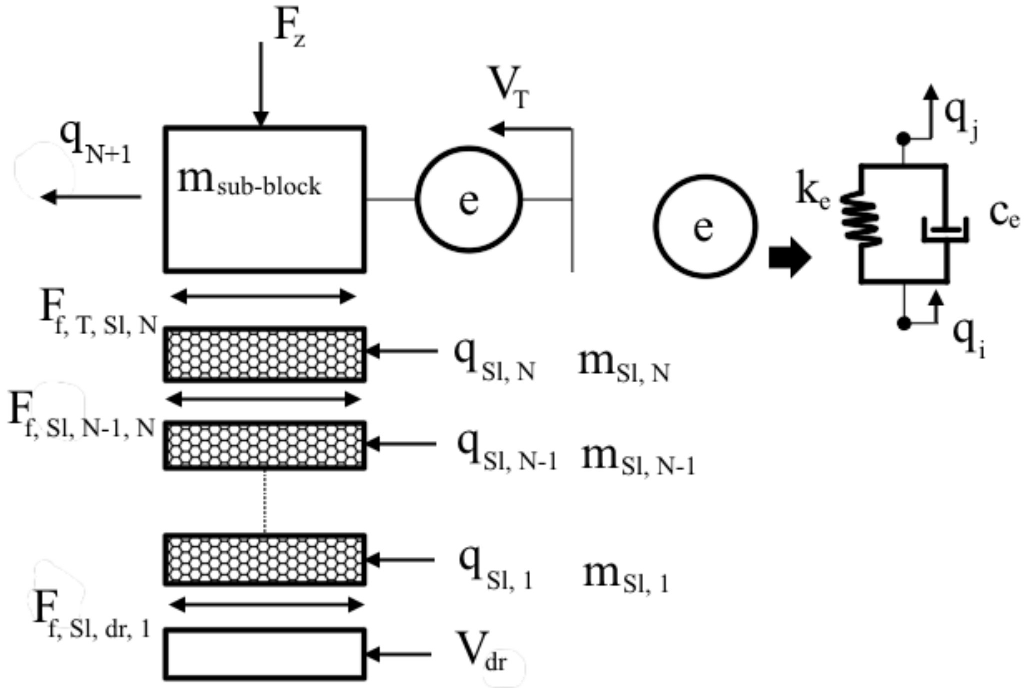


Fig. 3. Dynamic model of system: sub-block–slush layers–drum

The equation of motion for first (bottom) slush layer can be expressed as follows:

$$m_{Sl,1}(t)\ddot{q}_{Sl,1} = -\dot{m}_{Sl}(t)\dot{q}_{Sl,1} - c_{Sl,1}\dot{q}_{Sl,1} - F_{f,Sl,dr}(\dot{q}_{Sl,1}, V_{dr})sign(\dot{q}_{Sl,1} - V_{dr}) \quad , \tag{4}$$

where $m_{Sl,1}$ is the mass of slush and $c_{Sl,1}$ is the damping coefficient. The velocity of slush mass of first $\dot{m}_{Sl,1}$ layer is calculated as follows:

$$\dot{m}_{Sl,1} = \frac{dm_{Sl,1}}{dt} = \dot{\rho}_{Sl,1}V_{Sl,1} + \rho_{Sl,1}\dot{V}_{Sl,1}. \tag{5}$$

The friction force between the first layer of slush and drum can be expressed as follows:

$$F_{f,Sl,dr} = \mu_{Sl,1}\frac{dv_{Sl,1}}{dh}A_{Sl,1} \quad , \tag{6}$$

where $\mu_{Sl,1}$ is the dynamic viscosity of first slush layer.

The equation of motion for $i$-th slush layer is equal

$$\begin{aligned} m_{Sl,i}(t)\ddot{q}_{Sl,i} = &-F_{f,Sl,i-1,i}(\dot{q}_{Sl,i-1}, \dot{q}_{Sl,i})sign(\dot{q}_{Sl,i}, \dot{q}_{Sl,i-1}) - \\ &F_{f,Sl,i,i+1}(\dot{q}_{Sl,i}, \dot{q}_{Sl,i+1})sign(\dot{q}_{Sl,i}, -\dot{q}_{Sl,i+1}) - c_{Sl,i}\dot{q}_{Sl,i} - \dot{m}_{Sl,i}\dot{q}_{Sl,i}, \; i = 2,...,N-1. \end{aligned} \tag{7}$$

Then, the equation of motion for last (top) slush layer is equal:

$$\begin{aligned} m_{Sl,N}\ddot{q}_{Sl,N} = &-c_{Sl,N}\dot{q}_{Sl,N} - F_{f,Sl,N-1,N}(\dot{q}_{Sl,N-1}, \dot{q}_{Sl,N})sign(\dot{q}_{Sl,N} - \dot{q}_{Sl,N-1}) \\ &-F_{f,Sl,T}(\dot{q}_{Sl,N}, \dot{q}_{N+1})sign(\dot{q}_{Sl,N} - \dot{q}_{N+1}). \end{aligned} \tag{8}$$

The equation of motion of sub-block is equal:

$$\begin{aligned} m_{sub-block}\ddot{q}_{N+1} &= -k_e(q_{N+1} - V_T t) - c_e(\dot{q}_{N+1} - V_T) - \\ &-F_{f,Sl,T}(\dot{q}_{Sl,N}, \dot{q}_{Sl,N+1}) sign(\dot{q}_{N+1} - \dot{q}_{Sl,N}) + m_{sub-block}\omega_T R_{dyn} \sin\gamma \end{aligned}, \tag{9}$$

where $m_{sub-block}$ is the mass of sub-block, $k_e$ and $c_e$ are the stiffness and damping coefficients, respectively, and $\gamma$ is the angle between radius and centrifugal force direction, calculated as follows:

$$tg(\gamma) = \frac{q_{N+1} - V_T t}{R_{dyn}}. \tag{10}$$

The friction force between slush and tire was evaluated using the friction model presented in [19]. Then, friction force can be expressed as

$$\begin{aligned} &F_{f,Sl,T}(\dot{q}_{Sl,N}, \dot{q}_{Sl,N+1}, p) = F_z(t)(\mu_{v1}(\mu_{v0} - \mu_{p1})\cdot \\ &\cdot\exp(\gamma_p\,|\,\Delta v_{Sl}\,|)(\mu_{p1}(\mu_{p0} - \mu_{p1})\exp(\gamma_p\,|\,\Delta v_{Sl}\,|) \end{aligned}, \tag{11}$$

where $\Delta v_{Sl} = \dot{q}_{N+1} - \dot{q}_{Sl,N}$ is the difference between the slush velocities, $\mu_{v0}$, $\mu_{v1}$, $\mu_{p0}$, $\mu_{p1}$ are force coefficients, and $F_z(t)$ is the normal force of wheel load.

The obtained velocities of slush layers and friction forces allow us to determine the generated heat per time unit at each layer. This can provide additional information about how slush layers interact with each other.

## 3. RESULTS AND DISCUSSION

The tire–slush interaction measurement was conducted at about 48 km/h of drum speed. The tire pressure was 2.2 bar, with the camber angle of 0º. The wheel load was about 4000 N. The ambient temperature of surrounding area varied from 0 ºC to 1 ºC. The force coefficient as the ratio of longitudinal friction force ($F_x$) and normal force ($F_z$) was expressed and its variation during the measurement is presented in Fig. 4. The maximum value reached 0.3.

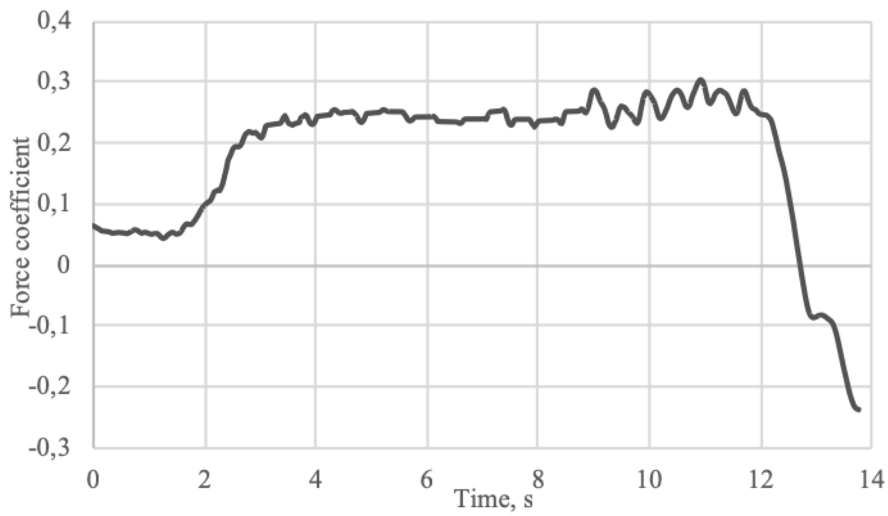


Fig. 4. Variation of longitudinal force coefficient

The sub-block load was expressed from measured normal force ($F_z$) and tire print was obtained at about 4200 N wheel load and 2.2 bar tire pressure. The normal force that pushes the tire tread block into the top layer of slush was determined. Its variation during the measurement is shown in Fig. 5.

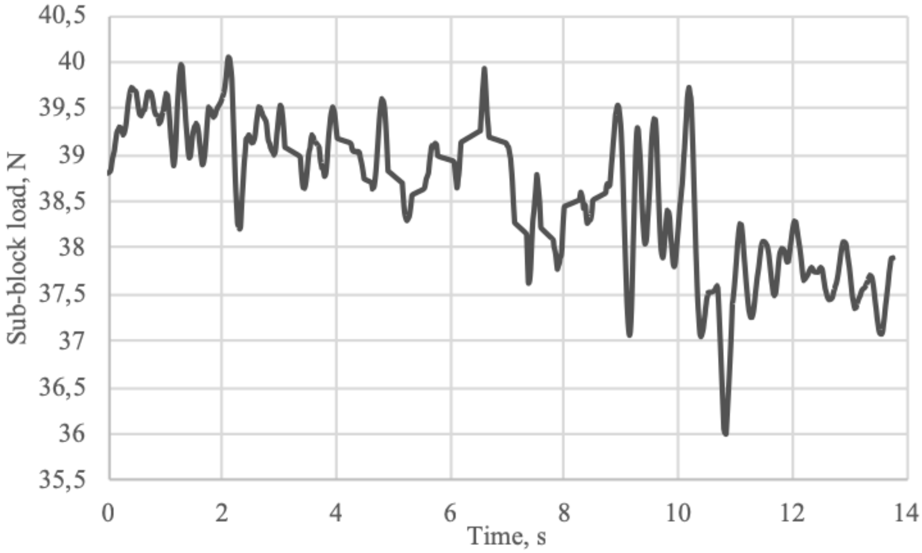


Fig. 5. Variation of sub-block load

To solve the motion equations derived in the second chapter, $\Delta t = 10^{-5}$ integration time was taken. The height of slush layer was divided into 9 elements, which varied from 40 mm (initial height) to 20 mm. The material of sub-block was assumed as a rubber, and density was taken equal to 1100 kg/m$^3$. The stiffness coefficient of rubber was taken $k_e = 19$ kN/m and damping coefficient equal to $c_e = 2.0$ Ns/m. The mass of sub-block was 0.88 g. The variation between 8th and 9th (top) layers velocities over time is shown in Fig. 6.

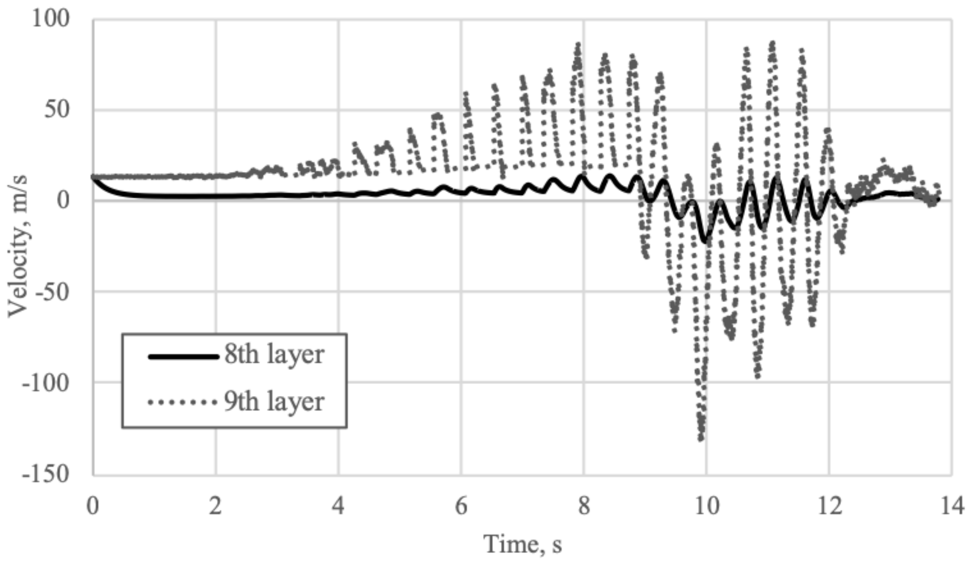


Fig. 6. Velocities of slush layers

Fig. 6 shows that the evaluated velocity of top slush layer, which is in direct contact with the tire, is higher than the layer below. This shows that the top layer of slush has highest influence on the friction mechanism between tire and slush. The velocity variation of sub-block over time is presented in Fig. 7.

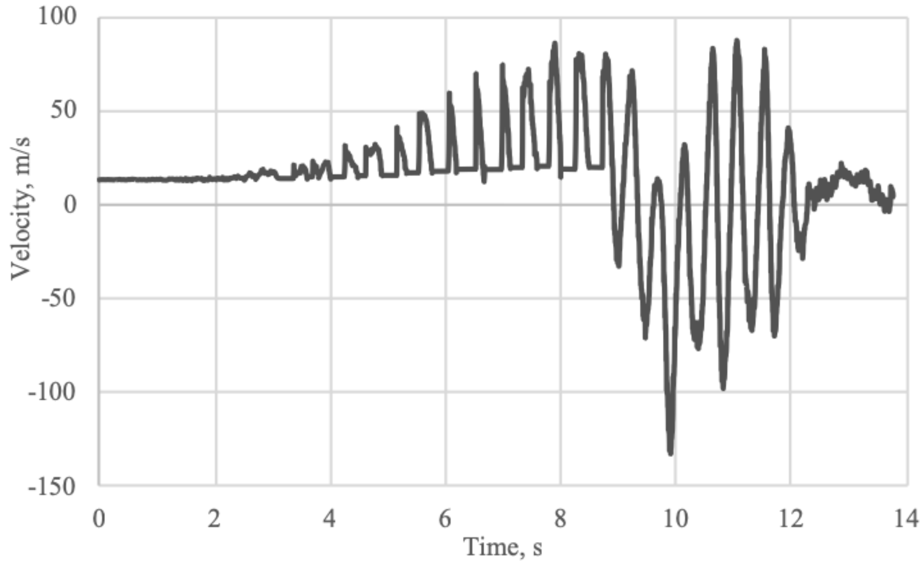


Fig. 7. Velocity of sub-block

The sub-block velocity fluctuation shown in Fig. 7 is similar to the velocity of top slush layer presented in Fig. 6. There is a slight difference between the values of velocities. It shows that there is a friction between the sub-block and the top layer of slush.

The developed mathematical model enables us to evaluate the heat flow at each slush layer. The variation between the heat flow at 8th and 4th layers over time is presented in Figs. 8 and 9, respectively.

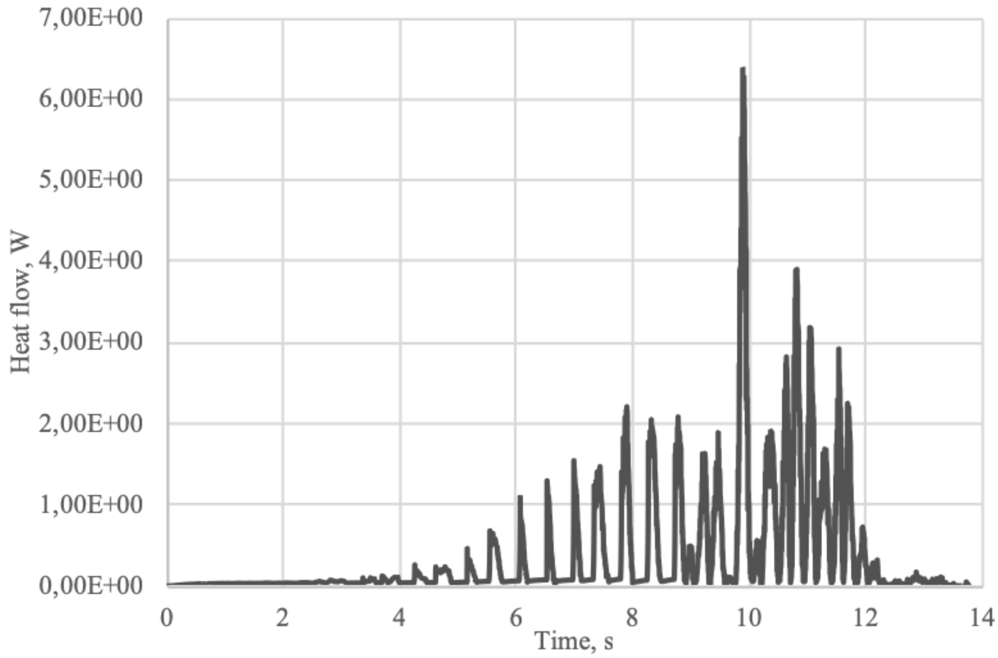


Fig. 8. Heat flow at the 8th slush layer

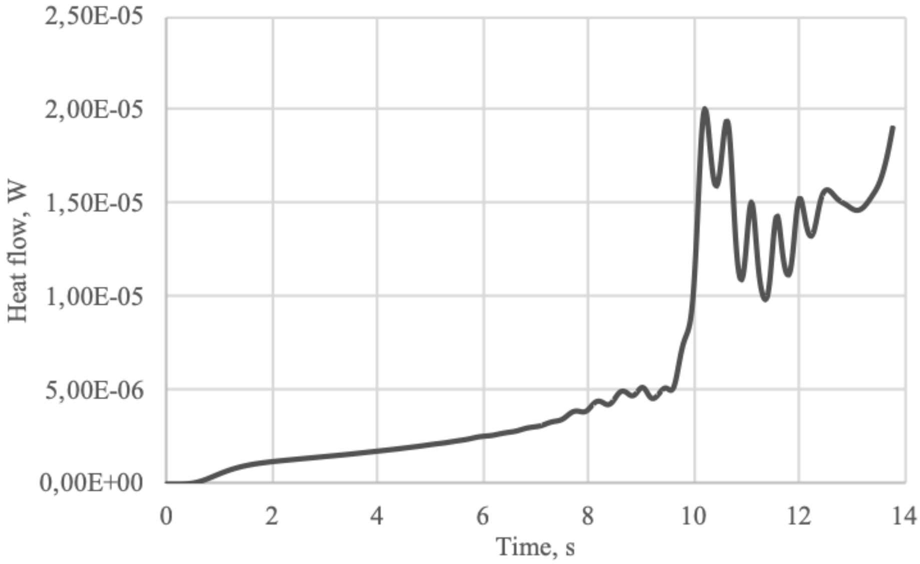


Fig. 9. Heat flow at the 4th slush layer

The performed heat generation analysis showed that highest heat value is generated at the top layer of slush, which is in direct contact with a tire. However, lower layers generate low heat values compared to the top layers. The value of generated heat decreases going from the top layers to the bottom.

## 4. CONCLUSIONS

This study has presented experimental and theoretical research of interaction between a tire and slush. The experimental study allowed us to determine the main parameters of tire–slush interaction as longitudinal friction force ($F_x$), normal force ($F_z$), tire angular velocity ($\omega_T$), tire dynamic radius ($R_{dyn}$), and slip ($S_x$). In the theoretical research, a mathematical model was created. The tire was analyzed at the micro-level and only one part of tire tread block – a sub-block – was analyzed focusing on slush behavior. Slush was analyzed as a multi-layer bulk and mass change velocity. The physical–mechanical properties of sub-block material and its mass were evaluated. The obtained velocities and friction forces of slush layers allowed us to calculate the heat generation at each slush layer. The results showed that the highest velocity and maximum heat generation were observed at the top layer of slush, which is in the direct contact with the tire.

**Acknowledgment**

This work has been supported by the Research Council of Lithuania Fund within the project "Investigation of tribological micro-macro processes in multi-phase layer with ice-snow particles and their contribution to tire-layer-surface system", project code P-MIP-17-233.

**References**

1. Usman, T. & Fu, L. & Moreno-Miranda, F.L. Quantifying safety benefit of winter road maintenance activities at an operational level. *Accident Analysis and Prevention*. 2010. Vol. 42. P. 1878-1887.

2. Usman, T. & Fu, L. & Moreno-Miranda, F.L. A dissagregate model for quantifying the safety effects of winter road maintenance activities at an operational level. *Accident Analysis and Prevention.* 2012. Vol. 48. P. 368-378.
3. Hayat, B.R. & Debbarh, M. & Antoniou, C. & Yannis, G. & et al. Explaining the road accident risk: weather effects. *Accident Analysis and Prevention*. 2013. Vol. 60. P. 456-465.
4. Seeherman, J. & Liu, Y. Effects of extraordinary snowfall on traffic safety. *Accident Analysis and Prevention*. 2015. Vol. 81. P. 194-203.
5. Sapragonas, J. & Keršys, A. & Makaras, R. & et al. Research of the influence of tire hydroplaning on directional stability of vehicle. *Transport*. 2014. Vol. 28. No. 8. P. 374-380.
6. Ripka, S. *Experimental investigation and modeling of tire tread block friction on ice*. PhD thesis. Leibniz Universitat Hannover. 2012. 111 p.
7. Ignatyev, A.P. & Ripka, S. & Mueller, N. & et al. Tire ABS-braking prediction with lab tests and friction simulations. *Tire Science and Technology*. 2015. Vol. 43. No. 4. P. 260-275.
8. Ripka, S. & Lind, H. & Wangenheim, M. & et al. Investigation of friction mechanisms of siped tire tread blocks on snowy and icy surfaces. *Tire Science and Technology*. 2012. Vol. 10. No. 1. P. 1-24.
9. Giessler, M. & Gauterin, F. & Wiese, K. & et al. Influence of friction heat on tire traction on andand snow. *Tire Science and Technology.* 2010. Vol. 38. No. 1. P. 4-23.
10. Lee, H.J. & Huang, D. & Johnson, H.T. & et al. Slip-based experimental studies of a vehicle interacting with natural snowy terrain. *Journal of Terramechanics*. 2012. Vol. 49. P. 233-244.
11. Bhoopalam, K.A. & Sandu, C. & Taheri, S. Experimental investigation of pneumatic tire performance on ice: Part 1 – Indoor study. *Journal of Terramechanics*. 2015. Vol. 60. P. 43-54.
12. Bhoopalam, K.A. & Sandu, C. & Taheri, S. Experimental investigation of pneumatic tire performance on ice: Part 2 – Outdoor study. *Journal of Terramechanics*. 2015. Vol. 60. P. 55-62.
13. Skouvaklis, G. & Blackford, R.J. & Koutsos, V. Friction of rubber on ice: A new machine, influence of rubber properties and sliding parameters. *Tribology International*. 2012. Vol. 49. P. 44-52.
14. Ella, S. & Formagne, Y.P. & Koutsos, V. & et al. Investigation of rubber friction on snow for tyres. *Tribology International*. 2013. Vol. 59. P. 292-301.
15. Klapproth, C. & Kessel, M. T. & Wiese, K. & et al. And advanced viscous model for rubber-ice friction. *Tribology International*. 2016. Vol. 99. P. 169-181.
16. Lee, H.J. & Huang, D. Vehicle wet snow interaction: testing, modeling and validation. *Journal of Terramechanics*. 2016. Vol. 67. P. 233-244.
17. Fiertz, C. & Armstrong, R.L. & Durand, Y. & Etchevers, P. & Greene, E. & McClung, D.M. & Nishimura, K. & Sayawali, P.K. & Sokratov, S.A. *The International Classification for Seasonal Snow on the Ground*. Technical Documents in Hydrology No. 83. IACS Contribution No. 1. UNESCO: Paris. 2009. 80 p.
18. Cruz, F. & Emam, S. & Prochnow, M. & et al. Rheophysics of dense granular materials: Discrete simulation of plane shear flows. *Physical Review E*. 2005. Vol. 72. P. 1-24.
19. Moldenhauer, P. *Modellierung un Simulation der Dynamik und des Kontakts von Reifenpofilblöcken.* PhD thesis. Technische Universität Bergakademie Freiberg. 2010. 152 p. [In Germany: Modelhaurer, P. *Modeling and simulation of the dynamics and the contact of tire tread blocks.* PhD thesis. Freiberg Technical University].

Received 12.11.2017; accepted in revised form 05.03.2019