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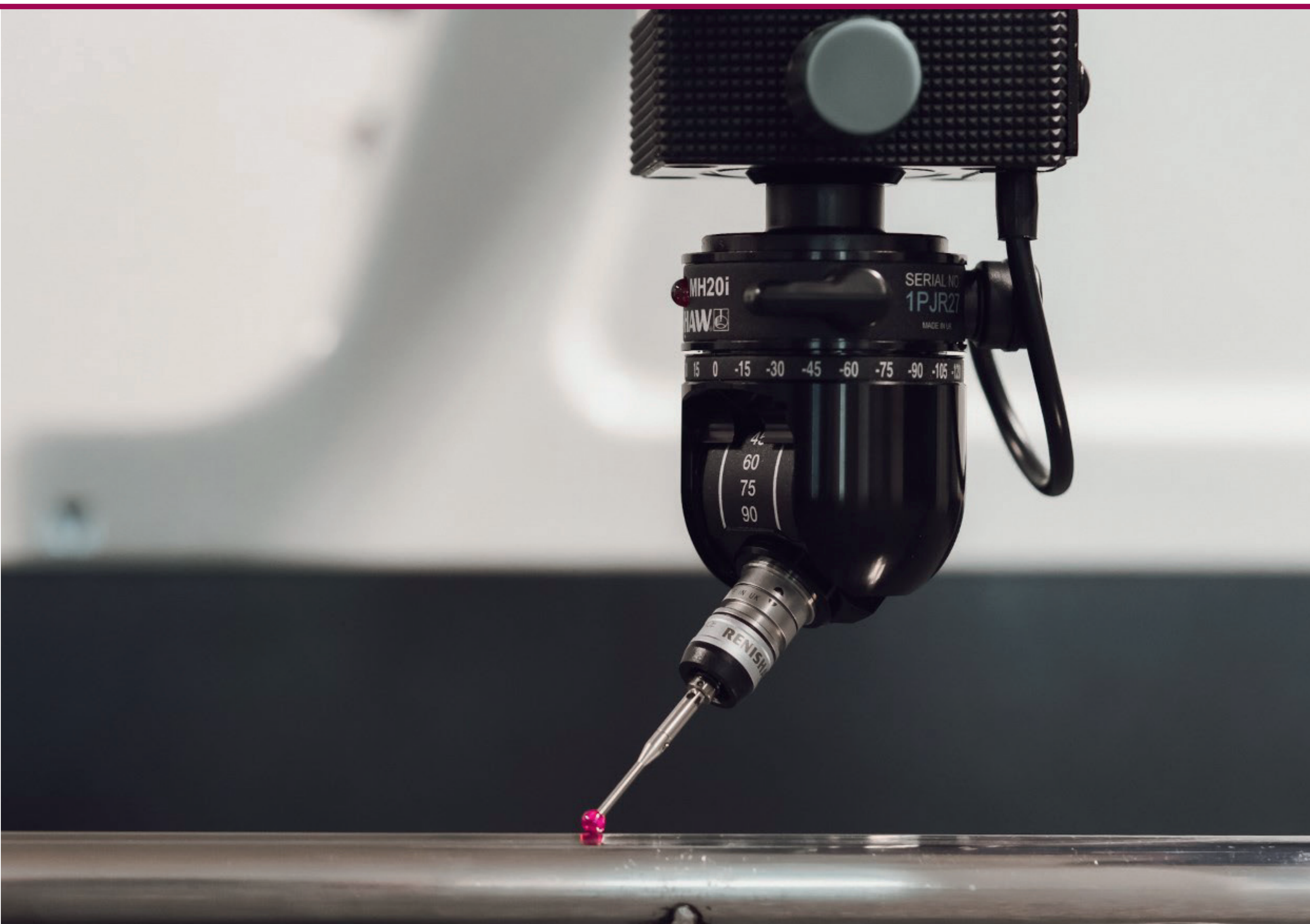
RIGA TECHNICAL UNIVERSITY

Ernests Jansons

INFLUENCE OF HUMIDITY, AIR AND ICE TEMPERATURE ON SLIDING ABILITY CHARACTERISTICS OF FRICTION PAIR STAINLESS STEEL-ICE

Summary of the Doctoral Thesis



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RIGA TECHNICAL UNIVERSITY
Faculty of Mechanical Engineering, Transport and Aeronautics
Institute of Mechanics and Mechanical Engineering

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Doctoral Student of the Study Programme "Production Technology"

INFLUENCE OF HUMIDITY, AIR AND ICE TEMPERATURE ON SLIDING ABILITY CHARACTERISTICS OF FRICTION PAIR STAINLESS STEEL-ICE

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on January 28, 2022 at the Faculty of Mechanical Engineering, Transport and Aeronautics of Riga Technical University, 6B Ķīpsalas Street, Room 417.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Ernests Jansons ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction, 4 chapters, Conclusions, 48 figures, 14 tables, 11 appendices; the total number of pages is 105, not including appendices. The Bibliography contains 104 titles.

TABLE OF CONTENTS

GENERAL CHARACTERISTICS OF THE THESIS

Actuality of the topic

The low coefficient of friction on ice is explained by the fact that a thin layer of water, or liquid-like layer, is formed between the sample sliding on the ice and the ice surface. The thickness of the liquid-like layer greatly influences the sliding ability [1]–[4]. Accordingly, the liquid-like layer thickness is influenced by the environmental conditions, the experimental sample, the ice, and the chosen method of measuring the friction pair system (see Fig. 1.2). Measuring the thickness of the liquid-like layer on the ice surface and accordingly predicting its effect on the sliding ability of the sample on the ice remains an unresolved issue for ice friction researchers.

Until now, scientists in ice-related studies [1],[5]–[14] have not fully defined the conditions under which the experiment takes place (see Table 1.1), primarily considering only the ice temperature as a parameter characterizing the experimental conditions. However, indicating only the ice temperature and without considering other parameters such as humidity and air temperature, which affect the thickness of the liquid-like layer and, consequently, the sliding of the sample on ice [15], give inexplicable experimental results and reduce comparability of studies of different authors. As a result, for example, if changes in the texture of the experimental sample surface are studied, significantly different results can be obtained with different methods of measuring the parameters characterizing sliding ability (sliding time, sliding speed, friction coefficient, etc.) at supposedly similar, insufficiently defined, experimental settings. In addition, there is no understanding of how the interaction of different environmental parameters affects the sliding of the sample on ice.

Considering the above, the Doctoral Thesis, which analyzed the impact of environmental conditions on the friction pair stainless steel-ice sliding ability and developed a prediction model that predicts sliding parameters depending on air and ice temperature and air humidity, is relevant.

Hypothesis: Air and ice temperature and air humidity interaction influence the sliding ability of friction pair stainless steel-ice. Knowing the influence of environmental parameters, it would be possible to predict the sliding ability charateristic parameters of friction pair stainless steel-ice depending on environmental conditions, as well as ensure the accuracy of measurements of sliding ability charateristic parameters and the reproducibility of the experiments.

Aim and objectives of the Thesis

The aim of the Doctoral Thesis is to determine the regularities between the sliding time and environmental parameters (air and ice temperature and humidity) for the friction pair stainless steel-ice to ensure the accuracy of measurements and the reproducibility of experiments in the on-field type experimental mode.

To achieve the aim, the following tasks have been completed:

1. Research and analysis of previous research.
2. Development of sliding time measurement procedure in on-field type experimental mode.
3. Experimental research.
4. Development of sliding time prediction model depending on the interaction of environmental parameters (air temperature, ice temperature, air humidity).
5. Development of sliding time measurement and prediction methodology.
6. Approbation of the prediction model and development of further research directions.

Research methods

In order to achieve the set aim and solve the tasks, quantitative and qualitative research methods were used, as well as the listed technical equipment for conducting experiments.

Empirically obtained tribological measurements were performed using a measuring device for determining the parameters characterizing surface sliding ability based on the principle of an inclined plane. During the development of the tribology measurement procedure, the subsequent quantitative studies were performed – the influence of ice texture and the influence of the surface texture of the sliding sample on the parameters characterizing the sliding ability and the experimental sample movement vibration analysis. Over time, visual observations of the ice surface and ice hardness measurements were performed with a nanoindenter *Hysitron TI980 (USA)* with an additional refrigeration module at the US company *"Bruker"*. In cooperation with *V-Research GmbH (Industrial Research and Development)*, tribological measurements were performed, measuring the influence of environmental parameters on the coefficient of friction using a linear tribometer – *RVM 1000 (Austria)*.

Surface texture measurements for experimental samples were performed using a *Taylor Hobson Form Talysurf Intra 50 (Taylor Hobson, UK)* contact type profilometer and laser scanning microscope *Confocal microscope VK-X250 / 260 (Keyence International NV / SA, Mechelen, Belgium)*. Skeleton runner geometry was measured with *a Mitutoyo CRYSTA-PLUS M500 (Mitutoyo, Japan)* manual coordinate measuring device. A portable microscope 1000x *USB Digital Microscope (Gaosuo, China)* was used to measure the ice surface texture, and an *Adobe Photoshop* computer program was used for data processing. Vibrations were measured using a portable accelerometer *X16-1D (GCDC, USA)*. Thermocouple *TP-122-100-MT-K (Czaki, Poland)* connected to *Proscan 520 (Dostmann, Germany)* was used to measure ice temperature. Air temperature and humidity were measured with *P330 Temp (Dostmann, Germany)*. Before the experiments, the runner temperature was measured with a *Thermal Imager Testo 871 (Testo, Germany).*

Statistical methods were used in data processing – descriptive statistics. An inferential statistical method for determining correlations was used to develop the prediction model – multifactor regression analysis and correlation analysis. The results were presented in the form of graphs, figures, and tables. *Solidworks 2019* computer program was used in the development of *CAD* models.

Scientific novelty

- It has been proved that the sliding of stainless steel on ice is influenced by the interaction of three parameters describing environmental conditions – air and ice temperature, air humidity – namely, providing high humidity (~90 %), ice temperature in the range of ~ –5 °C to –3 °C and air temperature in the range from ~ 0 °C to +4 °C, the optimal values of the sliding parameters are achieved by reducing the friction between the sample and the ice.
- A new model for predicting the parameters characterizing the friction pair stainless steel-ice sliding has been developed, including the interaction of three environmental parameters. Based on the model, a functional relationship has been developed that reduces an average percentage error of sliding time prediction by at least 40 %, which is better than using relevance that describes one (humidity or air temperature or ice temperature) environmental parameter determining the sliding time. Based on the prediction model, the methodology for measuring and predicting friction pair stainless steel-ice sliding ability characteristics was developed.
- It was found that in on-field experiments in the study range of surface texture of stainless steel sample (*Sa* 0.02–0.22 µm), there is no significant effect on sliding ability characteristics. In contrast, in control and stable laboratory conditions, sample surface texture affects the value of the coefficient of friction up to even 3.8 times.

Theses to be defended

- *Results of experimental studies describing the regularities of friction pair stainless steel-ice between environmental conditions and sliding time.* In the considered range of environmental conditions (relative air humidity 55 % to 95 %; air temperature –4 °C to +10 °C; ice temperature –6 °C to –1 °C), in the case of relative air humidity, a linear relevance was obtained, as the air humidity increases, the sliding time decreases. The 2nd order polynomial curve characterizes the results obtained for air temperature and ice temperature. As the temperature increases, the sliding time decreases, reaching the optimum value (air temperature ~ from +2 °C to +4 °C; ice temperature ~ from –4 °C to –3 °C), then the sliding time increases.
- *The developed sliding time prediction model, depending on the interaction of air and ice temperature and air humidity.* The interaction of the three environmental conditions used significantly influences the parameters characterizing the sliding of the sample (sliding time, sliding speed, friction coefficient, etc.) on ice. The sliding time prediction error was reduced by at least 40 % by using the developed prediction model.
- *The developed sliding time measurement and prediction methodology depending on environmental conditions.* The methodology provides guidelines for measurement procedures in the range of environmental conditions: relative humidity from 50 % to 95 %, air temperature from –4 °C to +10 °C, ice temperature from –6 °C to –1 °C. Using the methodology, the measurement results are within the absolute error limits: humidity

±4 %, air temperature ±1.5 °C, ice temperature ±1 °C, and sliding time ±0.01 s at a 95 % confidence level, which ensures the accuracy of the measurements. Using the developed methodology, the conformity assessment criteria of the prediction model fall within the limits that indicate the correct development of the model.

Practical significance of the thesis

The results obtained in the Thesis will prove that it is necessary to describe the conditions of ice friction experiments more fully. In ice research, it would be possible to increase the comparability between the works of different researchers. Knowledge of the interaction of environmental parameters on the stainless steel-ice sliding ability would provide a better qualitative study of other factors. For example, if the influence of environmental conditions is known, it is possible to more thoroughly analyze the influence of other stainless steel-ice parameters such as sample surface texture, pressure, shape, etc.

By developing the results, it would be possible to use them in ice-related industries, such as road maintenance, shipping, and representatives of ice sports, allowing the selection of appropriate runners, skates, which can provide advantages under certain conditions. The developed prediction model was used in Latvian skeleton training to predict the parameters characterizing skeleton sliding under certain environmental conditions, adjusting the runners accordingly. It is confirmed by the letter from the Latvian skeleton team coach D. Dukurs, Appendix 10 of the full version of the Doctoral Thesis.

Approbation of obtained results

Presentations in international scientific conferences *(total: 8, the most important are indicated)*

1. Jansons E., Irbe M., Kalniņa I., Gross K. A. The influence of environmental conditions on sliding over ice: An experimental study from bobsled push-start facility. 7th European Conference on Tribology, June 12–14, 2019, Vienna, Austria. *With a published thesis.*
2. Jansons E., Gross K. A., The Influence of Ice Topography on Sliding over Ice. ICTIE 2018: 20th International Conference on Tribology and Interface Engineering, November 14–15, 2018, Venice, Italy. *With a published thesis.*
3. Jansons E. Regularities of friction pair steel – ice sliding properties depending on ambient conditions. The RTU 60th International Scientific Conference. October 14, 2019, Riga, Latvia.
4. Jansons E., Boiko I. The Effect of Temperature and Humidity on Steel-Ice Sliding Ability. The RTU 61st International Scientific Conference on Mechanical Engineering and Technology and Heat Engineering. October 14, 2020, Riga, Latvia. *With a published thesis.*

Patent application

1. Jansons E., Lungevičs J., Boiko I. Portable sliding ability measurement device and method used in on-field type experiments. Pat. application No. LVP2020000098, 04.03.2021, owner – RTU.

Publications *(total: 12, the most important are indicated)*

Publications in scientific journals (indexed in SCOPUS)

1. Jansons, E., Irbe, M., Gross, K. A. influence of weather conditions on sliding over ice at a push-start bobsled facility. Biotribology, 2021, Vol. 25. ISSN 2352-5738. Available: doi.org/10.1016/j.biotri.2020.100152.
2. Lungevics, J., Jansons, E., Boiko, I., Velkavrh, I., Voyer, J., Wright, T. A Holistic Approach Towards Surface Topography Analyses for Ice Tribology Applications, Front. Mech. Eng. 7 (2021) 56. Available: doi.org/10.3389/FMECH.2021.691485.
3. Jansons, E., Lungevičs, J., Stiprais, K., Plūduma, L., Gross, K. A. Measurement of Sliding Velocity on Ice, as a Function of Temperature, Runner Load and Roughness, in a Skeleton Push-Start Facility. Cold Regions Science and Technology, 2018, Vol. 151, pp. 260–266. ISSN 0165-232X. Available: doi:10.1016/j.coldregions.2018.03.015.
4. Jansons, E., Gross, K. A., Lungevičs, J., Plūduma, L. The Influence of Ice Texture on Sliding Over Ice. Latvian Journal of Physics and Technical Sciences, 2018, Vol. 55, No. 5, pp. 54–64. ISSN 0868-8257. Available: doi:10.2478/lpts-2018-0036.

Publications in conference proceedings (indexed in SCOPUS)

1. Lungevičs, J., Jansons, E., Gross, K. Skeleton Runner Roughness and Surface Contact Area Influence on Sliding Ability: Field Experiments. Key Engineering Materials, Latvia, Riga, October 26, 2018. Switzerland: Trans Tech Publications Ltd., 2019, pp. 303–307. ISSN 1013-9826. e-ISSN 1662-9795. Available: doi:10.4028/www.scientific.net/KEM.800.303.
2. Jansons, E., Gross, K. The Impact of Ice Texture on Coefficient of Friction for Stainless Steel with Different Surface Roughness. Key Engineering Materials, Latvia, Riga, October 26, 2018. Switzerland: Trans Tech Publications Ltd., 2019, pp. 308–312. ISSN 1013-9826. e-ISSN 1662-9795. Available: doi:10.4028/www.scientific.net/KEM.800.308.
3. Velkavrh, I., Voyer, J., Wright T., Lungevičs J., Jansons, E., Boiko, I., Variations of ice friction regimes in relation to surface topography and applied operating parameters, IOP Conf. Ser. Mater. Sci. Eng. 1140 (2021) 012033. Available: https://doi.org/10.1088/1757-899X/1140/1/012033.

GLOSSARY

μ – coefficient of friction;
Ra – arithmetic mean deviation of roughness when measuring the profile, μm;
Sa – arithmetic mean deviation of roughness when measuring the surface, μm;
$b_0, b_1 \dots b_n$ – regression coefficients;
$x_1, x_2 \dots x_n$ – independent related variables;
σ – standard deviation;
RH – measured relative humidity, %;
T_{gaiss} – measured air temperature, °C;
T_{ledus} – measured ice temperature, °C;
T_{ks} – developed prediction model, friction pair stainless steel-ice sliding ability parameter, *s*;
r – correlation coefficient;
R^2 – coefficient of determination;
$\bar{R}^2$ – adjusted coefficient of determination;
σ_{reg} – standard deviation of a multivariate regression model.

Stainless steel – Uddeholm Ramax HH stainless steel used in the Thesis.
Ice – in the Thesis, where the liquid-like layer is not highlighted, the term (ice) denotes both the ice base and the layer formed on it.
Experimental or sliding sample – in the Thesis denotes a slider that is in contact with ice. Material, geometry, weight, etc., may vary.
Sliding parameters – in the Thesis denote the parameters by which the sliding ability of the sample on ice can be described. These can be sliding time, speed, coefficient of friction, etc.
Sliding time – in the Thesis denotes the experimentally measured total sliding time in a 24 m long section.
Field type or on-field experiments – in the Thesis denotes experiments that are performed outside the laboratory.
Environmental conditions – in the Thesis denotes relative humidity, air temperature, ice temperature.
Experimental session – in the Thesis denotes at least ten consecutive measurements of sliding time in the field type experimental mode.
IBSF – International Bobsleigh and Skeleton Federation.

1. LITERATURE REVIEW

1.1. Liquid-like layer and friction regimes as the sample slides on ice

A liquid-like layer forms on the surface of the ice, making the ice slippery and playing an essential role in the processes related to sliding on the ice. Historically, three main theories are distinguished relating to how a layer of water forms on the ice surface – pressure melting, surface melting or the formation of a liquid-like layer from free water molecules, frictional heating [15]–[18].

In ice friction, three friction regimes are distinguished – boundary friction, mixed friction, and hydrodynamic friction. Which friction regime is theoretically observed depends on the thickness of the liquid-like layer between the sample and the ice surface (see Fig. 1.1), [15], [19]. The thickness of the liquid-like layer, in turn, depends on the environmental conditions and experimental settings.

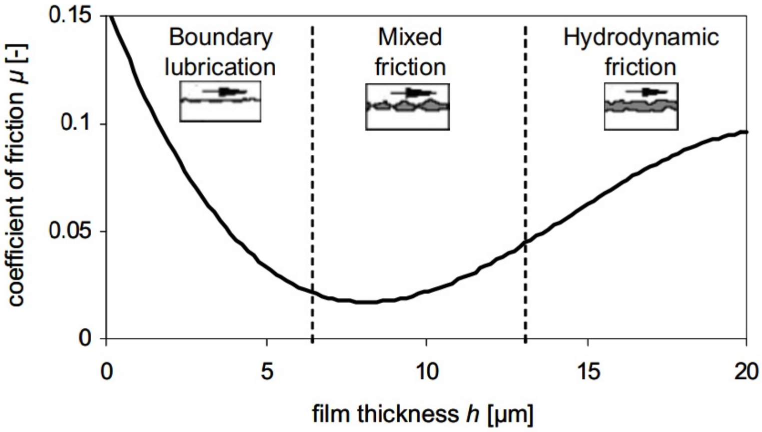

Fig. 1.1. Friction regimes relevant to ice friction depending on the thickness of the liquid-like layer [15], [19], [20].

The thickness of the liquid-like layer affects the coefficient of friction between the sliding sample and the ice. As the layer increases, the coefficient of friction decreases, transferring more direct contact between the ice ridges to the mixed contact between the ridges and the liquid-like layer until the optimum value is reached (see Fig. 1.1). The mixed friction regime in ice friction is considered the conditions [5], [10], [15], [19] that would provide the theoretically lowest coefficient of friction. At hydrodynamic friction, when the contact theoretically takes place only along the liquid-like layer, the coefficient of friction increases. It is explained by the viscous drag between the surface of the sample and the layer [15], [19].

1.2. Factors influencing the sliding of the sample on ice

Studies of stainless steel-ice and other friction pairs should consider both the sample sliding on ice, e.g. skating in hockey, speed skating, skeleton and bobsleigh, and the ice surface, which depends on the surrounding conditions: 1) environmental conditions; 2) conditions formed by mechanical action on the ice surface (see Fig. 1.2).

Several researchers have made significant contribution to the study of ice friction. The experiments have been performed under laboratory conditions, which provide stable and controllable environmental conditions, but there are limitations in size [5]–[8], [10], [21]. Experimental conditions, i.e. the applied force and sliding speed in the laboratory, are limited, which differs significantly from real-life situations. As far as possible, on-field type experiments provide adaptation of experiments to real-life situations, but they are mostly performed with human participation [11], [16], [22]–[24]. There are experiments where this is permissible and necessary. However, there must be maximum control over the experiment to ensure the high accuracy of the measurements when studying the sample sliding on ice.

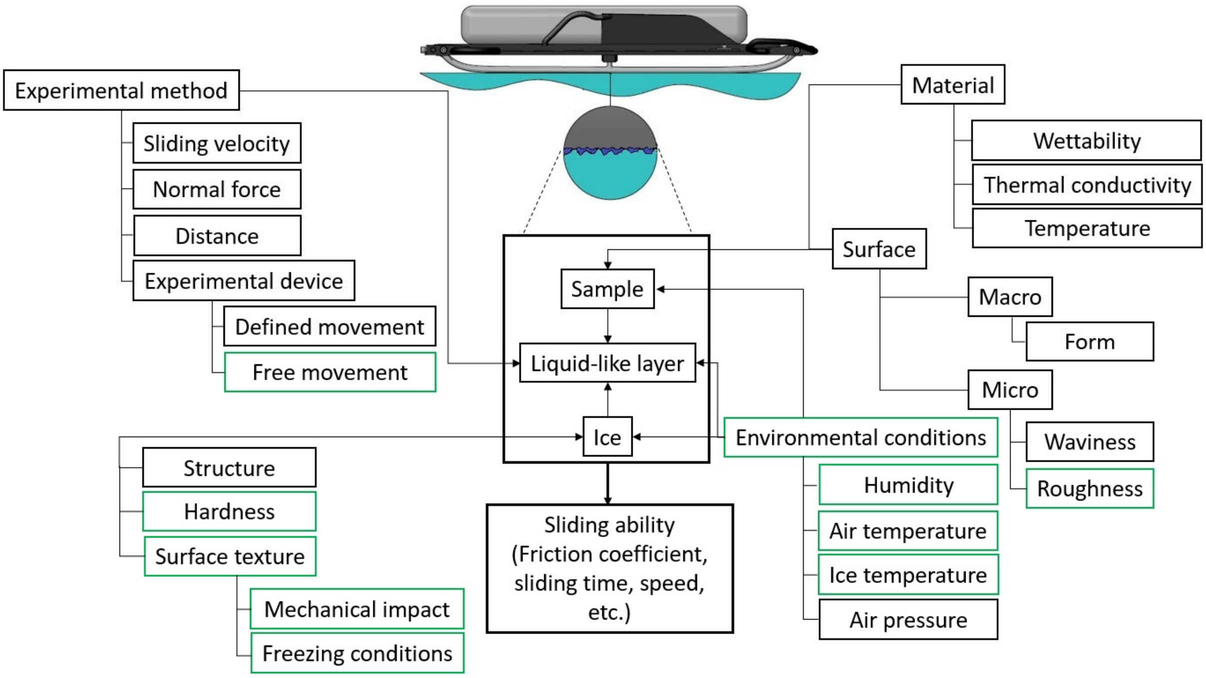

Fig. 1.2. Stainless steel-ice influencing factors (parameters highlighted in green were considered within the framework of this Doctoral Thesis).

Many factors influence the friction of the sample and ice, both of the sample sliding on the ice and of the ice; therefore, it is necessary to define the experimental conditions (see Fig. 1.2) carefully. The parameter like air humidity (see Table 1.1) is practically not measured. However, in the literature it has been mentioned that air humidity could have a significant effect on the sliding of the sample on the ice. Calabrese studied the effect of air humidity on the coefficient of friction of a stainless steel-ice friction pair at –29 °C, and the obtained data suggested that higher air humidity reduces the coefficient of friction [15]. According to the analysis of the known literature, there are no data on the effect of air humidity on the parameters characterizing sliding at other friction regimes. Humidity is the concentration of water vapor in the air. As it increases, water vapor in the air also increases. As air is in contact with surfaces, including ice, airborne water vapor molecules as a result of cohesion tend to mix with water molecules in the liquid-like layer due to intermolecular hydrogen bonds [25]. Given this aspect and Calabrese's study, humidity at all friction regimes should affect the thickness of the liquid-like layer and thus the sliding of the sample on ice.

Using regression analysis, studies have concluded that the temperature of a sliding sample has a more significant effect than the properties of the material, the sliding speed, and the load [6]. Ice temperature, which affects ice hardness, is mainly used as a determining parameter in defining conditions when developing theoretical models [26], [27] and carrying out practical experiments [7], [11], [12], [28]. Theoretically, under the same conditions, using different theories of ice friction, the values of the coefficient of friction can differ up to two times [3], [26]. The obtained experimental values vary in an even more extensive range [15], suggesting that the ice temperature as the only parameter describing the environmental conditions is insufficient. Given that theoretical models are inherently complex and include immeasurable parameters to describe ice friction, there is potential to use regression analysis based on empirically obtained experimental results.

Table 1.1

Summary of experiments performed by researchers

	Experiment	Reference	Sliding velocity, m/s	Environmental conditions		
				Air temperature, °C	Ice temperature, °C	Relative humidity, %
Experiments in laboratory	Ball against disc tribometer	Spagni [5]	0.25…1	–2; –6; –10; –13; –17	?	?
	Ball against disc micro tribometer	Scherge [7]	1…65	?	–6; –10; –17	?
	Ø 1,8 m tribometer	Baurle [8]	0.5…20	–20…1	–7…–5	?
	Ø 3,8 m tribometer	Scherge [9]	2.8…28	?	–12…–2	?
	Linear tribometer	Ducret [10]	0.003	–15…5	?	?
	Linear tribometer	Marmo [12]	0.01…0,4	?	–27…–0.5	?
	Linear tribometer	Bottcher [28]	1	?	–2; –6; –10	?
	Linear tribometer*	Rohm [29]	0.1…12	–2; –3.5; –6.3; –9.8	–3.2; –4.6; –7.4; –11,7*	79…82
	Rheometer	Kietzig [1]	0.1…1,2	–4	–14…–2	?
	Rotary type tribometer	Akkok [6]	0.05…5	–30…–10	–30…–10	?
	Rotary type tribometer	Liefferink [14]	0…1	?	–110…0	?
	Linear tribometer	Kim [13]	0.003	?	–18…–2	?
On-field experiments	Frame with four bobsleigh runners	Poirier [11]	1…10	?	–4.6…–2.2	?
	A man on skates	Koning [22]	4…11	12	–11…–2	55
	A man on skates	Colbeck [23]	?	?	–13.5…–2.5	?
	Frame with skates	Federolf [24]	1…2	14…16	–6…–5	17…26
Number of cases				**8 from 16**	**14 from 16**	**3 from 16**

** – experiments were performed on compressed snow instead of ice.*

Based on the literature analysis, it can be concluded that in most cases, a complete description of the settings of ice friction experiments is not performed. The interaction of three environmental conditions (air temperature, ice temperature, and air humidity) can significantly affect the sliding parameters between the sample and the ice. Knowing the potential impact of these conditions on the result could reduce inaccuracies in already complex ice friction studies at the root and improve comparability between works by different authors.

2. EXPERIMENTAL RESEARCH

2.1. Apparatus for measuring the sliding parameters of an experimental sample

Considering the reviewed literature and technological support, to obtain the experimental conditions as close as possible to real-life situations, on-field type experiments must be performed. After analysis of the literature, to use it successfully, it must be ensured that the human factor cannot affect the sliding measurements. There must be a controlled trajectory, and the environmental conditions must be fully described.

Sliding parameters measuring device

On-field type experiments were performed using a measuring device based on the inclined plane principle in bobsleigh, skeleton, and luge start training trestle. The trestle is partially closed, preventing exposure to wind, snow, rain, and direct sunlight, but the air temperature and humidity directly depend on environmental conditions. The trestle is divided into the luge start training trestle and the bobsleigh, skeleton training trestle. The luge start training side was used in the experiments (total distance – 24 m), because it is possible to fix the starting position of the experimental sample without major modifications, as well as the angle of inclination (~14°) that ensures the start of the sample from steady-state at any experimental environmental conditions (see Fig. 2.1). The section has four optical sensors that record the sliding time and start and end speed (see Fig. 2.1 a)).

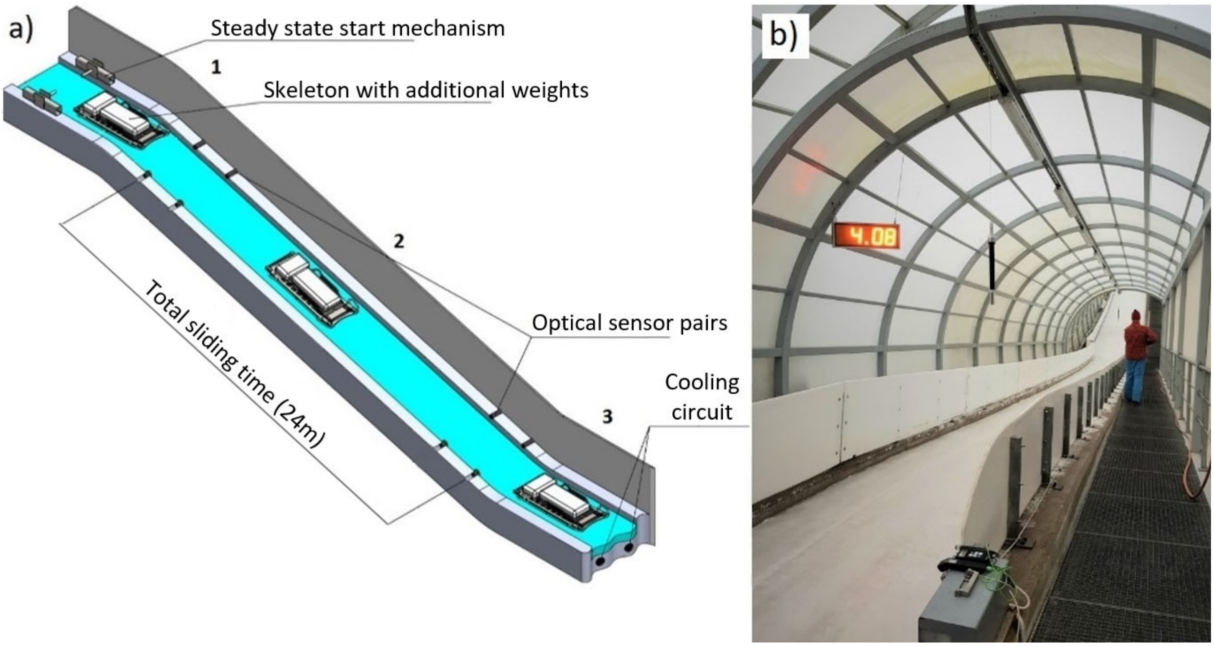

Fig. 2.1. Luge start training trestle: a) CAD scheme; b) photo.

Ice freezing was performed with a built-in refrigeration system. Obtaining the required thickness of the ice layer, it was treated with a custom planer, smoothing its surface. To ensure the stability of the trajectory of the sample, a groove of Ø20 mm was embedded in the ice surface parallel to the sliding direction, which ensures a controlled movement along with it (see Fig. 2.2 b)).

Experimental sample

A skeleton with two runners was used in the experiments. Runner diameter was 16 mm, length ~1 m. The runners are designed following the *2019 IBSF* standard [30]: material – stainless steel *Uddeholm Ramax HH*. The runners at the skeleton were tightened with a curvature adjustment screw, thus changing the theoretical contact area and the height of the skeleton from the ice surface [31]. The tension was chosen to be 9 mm from the "zero" tension (the runners are not tensioned) to obtain a radius of ~11500 m (measured with the *Mitutoyo CRYSTA-PLUS M500 (Mitutoyo, Japan)* manual coordinate measuring device). The size was controlled with a depth gauge (reading accuracy 0.05 mm). This tension provides close proximity to the racing mode and skeleton control – higher tension makes the skeleton less controllable and can increase the number of random errors.

The skeleton runners were polished by hand using 600, 1500, and 3000 *3M* fabric-based sandpaper until a mirror-smooth surface (*Sa* ~ 0.03 µm) was obtained. 600 *3M* sandpaper was used to obtain scratched runners, and the runners were scratched with a constant scratching force and path [32], [33], obtaining *Sa* ~ 0.12 µm. Texture measurements were performed according to *EN ISO 25178* [34], using a *Taylor Hobson Form Talysurf Intra 50 (Taylor Hobson, UK)* profilometer.

Experimental conditions

In order to provide closer conditions for the racing mode, an additional weight of 65 kg was added to the skeleton, which corresponds to the weight of female and lighter male athletes, reaching the total weight of the experimental sample – 95 kg. Additional mass was provided by sandbags, which were glued to the sample in a constant position (see Fig. 2.2 a)). The effect of the applied force on sliding ability is discussed in [33]. The starting position of the experimental sample was kept constant in various experiments using a chain. Before the sample was released from the steady-state position, the chain on the handle and the chain attached to the sample was connected by the pin and tensioned. The experimental sample starts to move when the pin between the chains is pulled out.

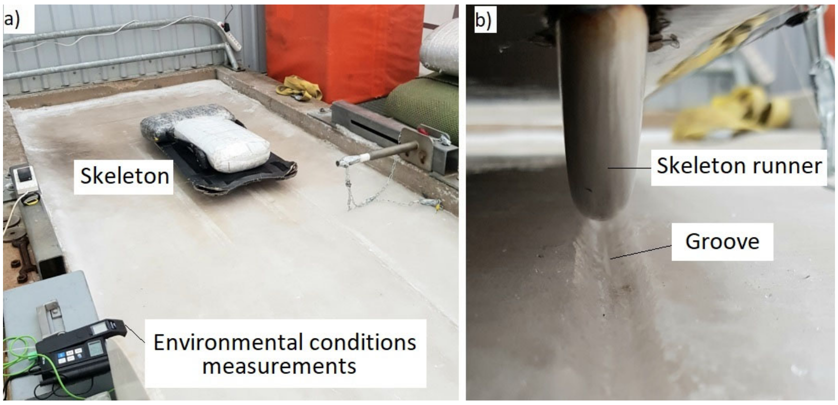

Fig. 2.2. Representation of the experimental sample on the start training trestle: a) skeleton before the experiments and measuring instruments of environmental conditions; (b) the skeleton runner in the embedded ice groove.

At least ten sliding time measurements were performed in each experimental session. It is generally accepted that the descriptive parameter of sliding ability is the coefficient of friction [5], [7], [15], [29]. In this case, the sliding time was measured (a shorter sliding time is equivalent to a lower coefficient of friction).

Measurements of environmental conditions

Ice temperature was measured using a contact type thermocouple *TP-122-100-MT-K (Czaki, Poland)* connected to a *Proscan 520 (Dostmann, Germany)* thermometer. In ice friction studies, the ice temperature tends to be assumed depending on the ice temperature set in the experiments, without specifying the measurement method [10], [35], [36] or assuming post-air temperature in the freezing chamber [5]. In other cases, thermocouples are used [8], [28], [29]. Air temperature and humidity were measured with a *P330 Temp (Dostmann electronic, Germany)* thermometer. Both devices were placed in the same position during the experiments (see Fig. 2.2 a)). Measurements of environmental conditions were recorded before each sliding time measurement in the experimental session. The runners' temperature was measured with a *Thermal imager Testo 871 (Testo, Germany)*.

2.2. Ice surface research

The experiments were performed with nanoindenter *Hysitron TI980 (USA)* with an additional refrigeration module at *Bruker* in Minnesota, USA, within the framework of the USA international mobility programme. The summary of the Doctoral Thesis deals with the visual changes of the ice surface at different ice temperatures. Measurements of ice hardness and liquid-like layer thickness are discussed in the full version of the Thesis.

The terms – rougher and smoother ice surface – have only a visual basis and are used to describe the observations. Two experiments were performed: in Experiment No. 1, ice was frozen at –4 °C and kept at –15 °C for 1 hour (Fig. 2.3 a)). When frozen, the boundaries of crystals are clearly visible and the surface is smooth. As the observations continue, the boundaries of crystals become more challenging to determine, and the surface looks rougher than when frozen. In Experiment No. 2, the ice was frozen at –15 °C and kept at –4 °C for 1 hour (Fig. 2.3 b)). Compared to Experiment No. 1, more and smaller crystals are visible at the time of freezing, but as the observations continue, the crystal boundaries converge, and larger, smoother crystals form.

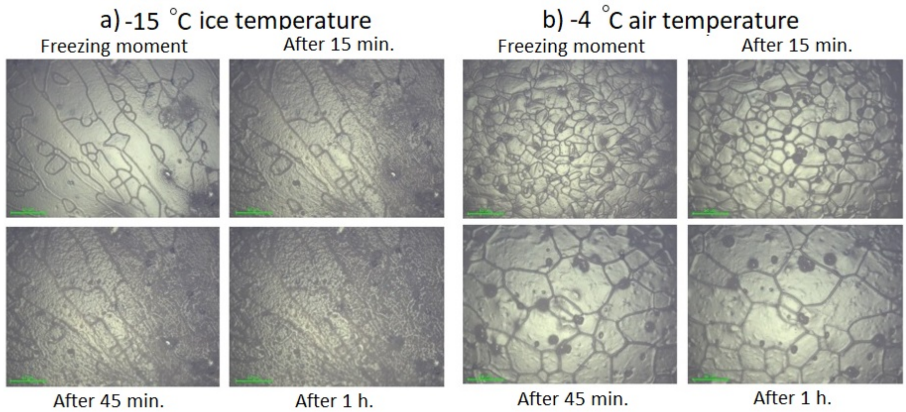

Fig. 2.3. Ice surface observations: (a) at ice temperature of –15 ° C; (b) at ice temperature of –4 ° C.

After observations under two different conditions, it can be concluded that the ice surface becomes rougher at lower ice temperatures. It is possible that the thin layer of water on the surface freezes, but at warmer temperatures, the water layer remains and promotes crystal fusion and a smoother ice surface.

2.3. Effect of ice texture on sample sliding on ice

Given that environmental conditions and mechanical action on the ice surface can cause changes in the ice surface texture, different types of ice surfaces (smooth, scratched, and with water droplets (see Appendix 4 of the Doctoral Thesis)) were specially developed and their effect on the sliding time of the sample was experimentally tested.

The procedure of ice preparation for obtaining different types of ice surfaces is described in [37], [38]. Ice treatment was performed along the entire length of the trestle, both in the groove and on the smooth ice surface. Sliding time measurements were performed on the prepared three ice surfaces on three different experimental days, each showing a similar trend; therefore, the graphical representation (Fig. 2.4 (a)) is indicated for only one experimental day with the following conditions – ice temp. –8 °C; air temp. –7 °C; relative humidity 69 %. According to the graph, it can be seen that on all ice surfaces there is a tendency for the sliding time to decrease in the first three measurements and then to stabilize.

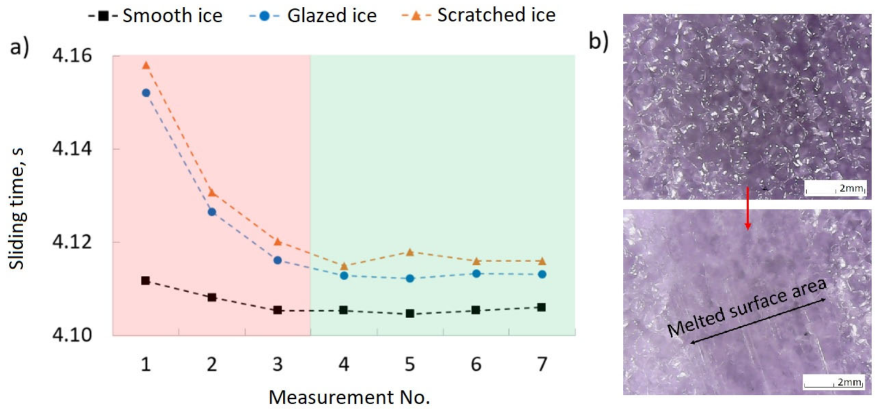

Fig. 2.4. (a) – Effect of ice surface on experimental sample sliding time; (b) – changes of ice surface before and after one measurement.

The ice surface was examined with a *1000x USB Digital Microscope portable microscope (Gaosuo, China)* to determine changes before and after one measurement (see Fig. 2.4 (b)) of ice with droplets. It can be seen that there are marked traces of sliding and deformation of the surface texture. As the skeleton slides, it may consume energy by smoothing the surface of the ice texture until it is smooth and the sliding time stabilizes [39].

In this work, the emphasis is on on-field type experiments. However, by studying how the ice surface affects the sliding speed and static coefficient of friction under laboratory conditions, with lighter samples, it was found that ice with water droplets provides the lowest coefficient of friction [37], [40]. This was explained by the theoretically small contact area between the ice and the sample, so the adhesion force is less pronounced, and the smaller sample mass provides movement over the ice surface rather than energy consumption to level the surface. Theoretically, if higher droplet hardness were provided, it is possible that the sliding results in Fig. 2.4 would be the opposite.

The experiment showed that the ice layer could significantly affect the sliding ability. At least three "test" measurements are required, which are not considered before the actual experiment is started.

2.4. Vibration analysis of the experimental sample

Vibration analysis was performed as the experimental sample slide along the ice track. Data were obtained with a 3-axis accelerometer *X16-1D (USA)*. The accelerometer was mounted below the sample in the center of mass. As the skeleton slid down the ice track, accelerations were measured in the sliding direction (x-axis), transverse direction (y-axis), and vertical direction (z-axis). The data were recorded for 5 seconds, which is required for the skeleton to cover the entire 24 m distance from the first optical sensor to the last section of ice used.

The experiments were performed on two significantly different days of experiments (Experiment No. 1: air temperature and ice temperature is –10.5 °C, relative air humidity 70 % – possible *boundary friction regime*. Eperiment No. 2: air temperature is 2 °C; ice temperature –4 °C, relative humidity 70 % – possible *mixed friction regime*) obtaining information on the track profile, ice and groove quality, and the effect of vibrations on the parameters characterizing sliding under different environmental conditions (different friction regimes). The following text uses the terms *boundary friction regime* and *mixed friction regime* to describe both experiments. The selected terms are for explanatory purposes only, based on the ice friction regime curve (Fig. 1.1).

The track profile was measured providing information that there is a significant rounding at the end. In addition, as the sliding speed increases, the amplitude of the acceleration oscillations tends to increase, so there may be inaccuracies in the measurements of the obtained parameters at higher sliding speeds. In the mixed friction regime, the values of the acceleration standard deviation in both the sliding and vertical directions are ~20 % lower than in the boundary friction regime, which indicates a "calmer" skeleton sliding, which can affect the sliding time measurements, respectively. Transverse acceleration measurements indicate the potential groove effect on sliding ability. In contrast to the accelerations in the x and z-axis directions, the standard deviation in the y-axis direction for acceleration measurements was smaller at the boundary friction regime than at the mixed friction regime (difference ~10 %). Such an observation could indicate a higher quality of the groove as the ice temperature decreases. The increase in ice hardness could explain this.

More information and figures are given in the full version of the Doctoral Thesis and in [32].

2.5. Influence of the surface texture of the experimental sample on sliding over ice

Since the experimental sample runners were hand-treated before the experiments and no surface quality control was performed before each experiment, the effect of unwanted scratches on the runner surface on the sliding time was investigated. Five experiments were performed under different environmental conditions. Initially, the tracks were polished to obtain a surface roughness of *Sa* ~ 0.03 µm ± 0.01 µm. An experiment with at least ten measurements was performed to obtain a sliding time. Then the same runners were scratched in the direction of movement with a 600 *3M* sandpaper [33], obtaining a surface roughness *Sa* ~ 0.12 µm ± 0.03 µm, and the experimental procedure was repeated.

The mean percentage difference between the sliding time results with polished and scratched runners reached 0.07 % (within the standard deviation of the measurements). The average % difference in sliding time between experimental days was 0.77 %.

As proved in various publications [5], [15], [29], [41], [42], the surface texture of the sliding sample can significantly affect the sliding results. However, the experimental conditions – applied force and speed – are drastically different compared to on-field type experiments;

therefore, environmental conditions have a more significant effect on sliding results than the runners' surface roughness in the range considered.

More information and figures are given in the full version of the Doctoral Thesis and in [32].

2.6. On-field experimental procedure

Based on the experimentally obtained data, a procedure for performing on-field type experiments was developed. A full description of the experimental procedure, including the necessary measuring instruments and equipment is described in the full version of the Thesis and in Appendix No. 11. By performing direct measurements using optical sensors a parameter characterizing sliding is obtained – sliding time, s.

1. Description of the measurement procedure

Algorithm of measurement procedure in Fig. 2.5.

The section on ice surface preparation describes the steps of treating the ice surface before starting the experiments, assuming that the ice surface with the built-in groove parallel to the direction of motion has been prepared in advance. The part on experimental sample and runner preparation describes how to prepare the runners (*Sa* in the range of 0.02 µm to 0.15 µm (measured according to *EN ISO 25178* [34])), what tension to be used (radius of curvature ~11500 m, or 9 mm from "zero" tension), an additional mass (65 kg) is added and described what and for how long (10–15 minutes) must be observed when placing the sample on the ice surface for cooling.

The section on experimental sequence describes the step-by-step sequence of how an experiment is performed, assuming that the steps described above have been performed. Initially, devices for measuring environmental conditions are installed, as well as the operation of optical sensors is checked. The necessary additional equipment is then installed to ensure that the experimental sample is released from the steady-state position as well as returned to the starting position. Once the experimental preparation process is complete, the sliding time measurements are taken.

After one experimental session, if necessary, appropriate manipulations can be performed, for example, for runners, ice track, experimental sample.

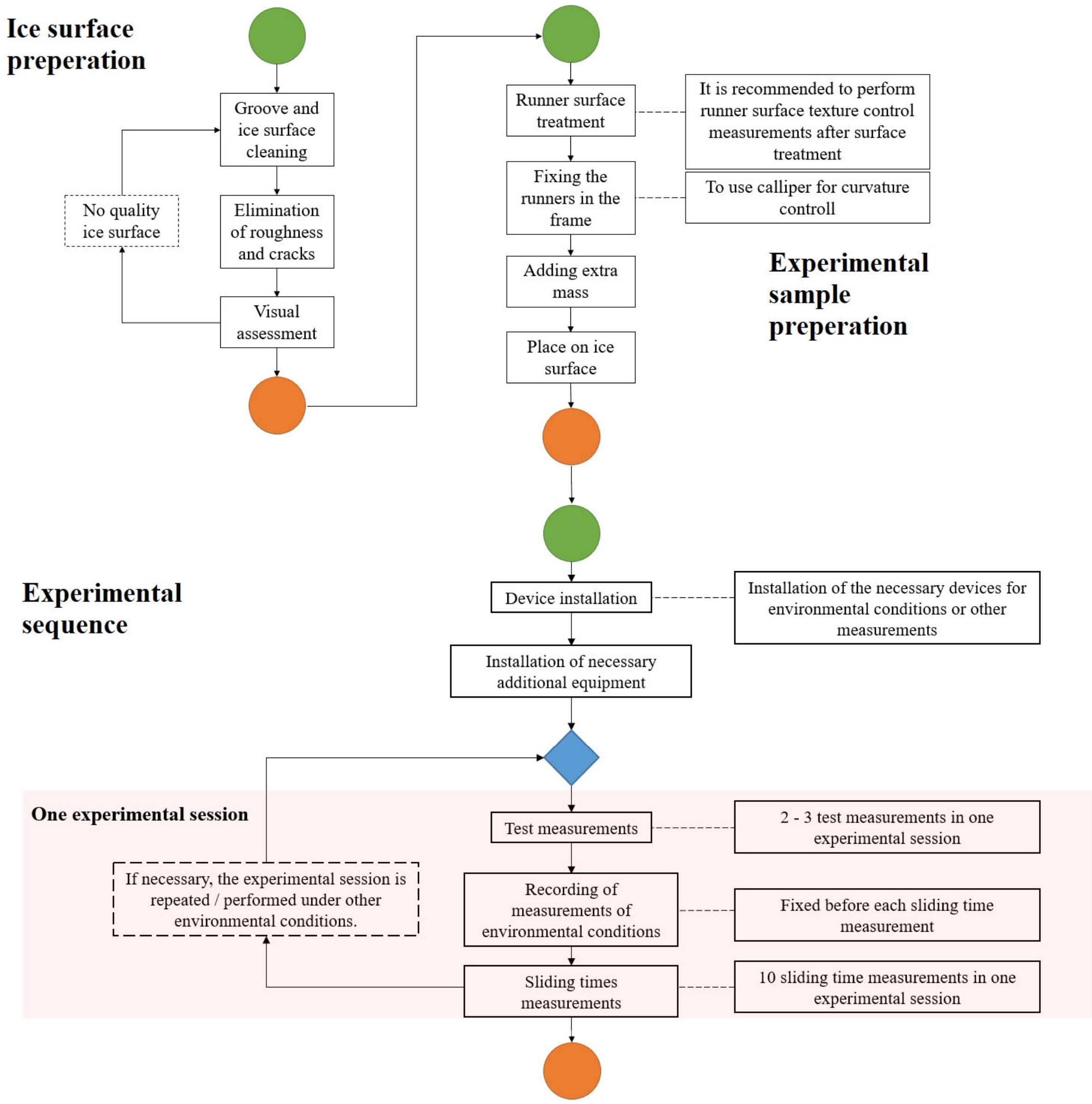

Fig. 2.5. Algorithm of the procedure for measuring the parameters characterizing the friction pair stainless steel-ice sliding ability (divided into three consecutive parts).

2. Criteria for evaluating the field type experimental procedure

Several criteria can be set to assess the quality of the on-field type experimental procedure performed (in this case, based on the explanations of terms in standard *EN ISO 9000: 2005* [43]). They must be fulfilled so that the measurement data obtained can be used for further processing. The proposed criteria for evaluating the experimental procedure are as follows:

- runner surface roughness characteristic parameter *Sa* in the range from 0.02 μm to 0.15 μm (measured according to standard *EN ISO 25178* [34]);
- the absolute error of one experimental session of environmental conditions for relative air humidity ±5 %, air temperature ±2 °C, ice temperature ±1 °C;
- the absolute error of the total sliding time of one session does not exceed ±0.01 s;
- the total experiment time per session should be less than 20 min.

If the experimental session is longer, given that the experiments are performed in the on-field type experimental mode, one of the environmental conditions may change significantly, influencing the measured sliding time accordingly.

3. Comparison of on-field type experimental procedures

The developed on-field type experimental procedure was compared with the experimental procedures found in the known literature, which could theoretically ensure the study of the effect of environmental conditions on the friction pair of stainless steel-ice (see Table 2.1).

Table 2.1

Comparison of experimental procedures

Experimental procedure	The human factor is excluded	Controlled trajectory	Control of environmental conditions	Possibilities of variation
Federolf experiments [24]	Yes	No	Yes	Yes
Poirier experiments [11]	No	No	No	Partly
Hainzlmaier experiments [16]	No	No	No	No
Developed procedure	Yes	Yes	Yes	Partly

The data in Table 2.1 show that the experimental procedures of Poirier [11] and Hainzlmaier [16] cannot be used in this case. The human factor directly affects the results of experiments; thus the trajectory of movement can differ significantly. Complete control of environmental conditions could be performed in Poirier experiments. However, in the case of Hainzlmaier, the whole bobsleigh track is used, where environmental conditions may differ in different parts of the ice track, and it is not protected from climatic conditions. Federolf's [24] experimental procedure would be the most appropriate, but it would not control the trajectory of the experimental sample, which would lead to inaccuracies in the results. The developed procedure requires a specific infrastructure, but it can meet the set criteria.

2.7. Influence of environmental conditions on sliding time

As the experiments were performed in the on-field conditions, the control of environmental conditions was not possible. Therefore, only those experiments where the observed environmental conditions differed were taken into account for further analysis (14 in total). Measurements were performed according to the procedure described above. Measurement full results are displayed in Table 2.6 in the full version of the Doctoral Thesis.

The results were analyzed as independent parameters – the influence of air humidity, air temperature, and ice temperature on the sliding time (see Fig. 2.6) and the interaction of 3 parameters on the sliding time (see Fig. 2.7). In Fig. 2.6, each measured environmental condition parameter was compared with the sliding time, thus obtaining correlations that would be obtained if only one of the three descriptive parameters of the environmental conditions were measured. However, the other parameters also changed from experiment to experiment. Using the possibilities of *Microsoft Excel 2017*, a curve was obtained for each case, which describes the specific relevance most closely [44]. The coefficient of determination R^2 was used to assess the closeness of the relevance [45].

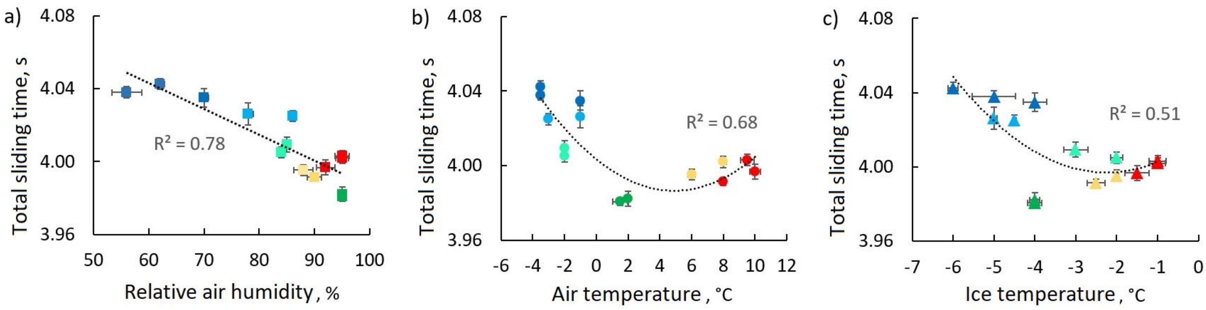

Fig. 2.6. Sliding times depending on environmental conditions: sliding time dependence on (a) relative humidity; b) air temperature; c) ice temperature [32].

In order to obtain more information about the experimental conditions and their relation to the sliding time, Fig. 2.7 was created. The sliding time is shown in bars and arranged based on ambient conditions from colder and drier to warmer and wetter. Theoretical friction regimes (based on [15], [19], [20] and Fig. 1.1) are added for a more precise explanation of the results. Blue indicates the region where the friction theoretically approaches the boundary friction regime, green indicates the mixed friction regime, and red indicates the hydrodynamic regime.

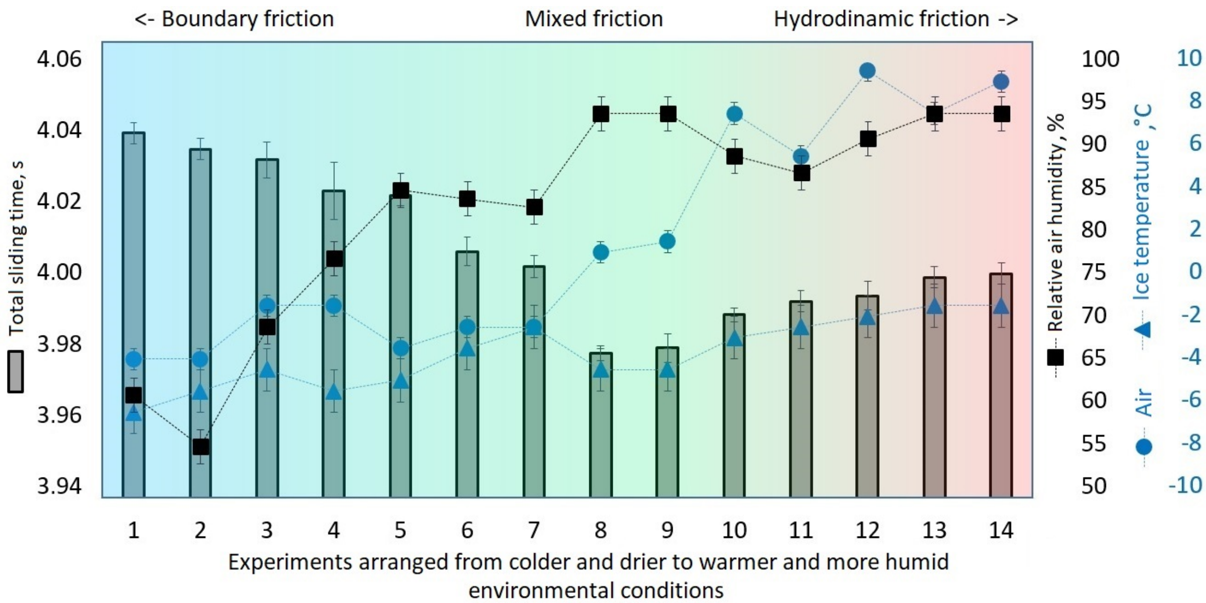

Fig. 2.7. Sliding time depending on air temperature, ice temperature, and relative humidity. *Based on the ice friction curve, the experiments are arranged from colder and drier to warmer and wetter conditions* [32].

The lowest sliding time was obtained in experiments 8 and 9 when the air humidity is the highest (~95 %), air temperature is ~2 °C, and ice temp. ~ –4 °C (see Fig. 2.7). This region was adopted as the mixed friction regime based on the friction regimes, which provides the fastest sliding conditions [11]. For experiments 10 to 14, the sliding times are similar. Due to high air and ice temperatures, this region was adopted as a hydrodynamic friction regime. As the humidity and temperatures fall from experiment 7 to experiment 1, the sliding time increases.

As observed in the sample vibration analysis experiments, changes in the amplitude of oscillations in the case of possible boundary friction and mixed friction were observed in about 20 % of on on-field type experimental mode. Thus the sliding time under colder conditions may be indirectly affected by higher vibrations. This observation can be explained by the results of Seymour-Pierce experiments [39]. Higher vibrations at colder environmental conditions may occur due to cracks and roughness of the ice surface formed from previous experiments. Accordingly, in warmer conditions, the movement of the skeleton down the ice route contributes to the melting of the liquid-like layer and the decrease of surface hardness, which, in turn, leads to surface recrystallization and a smoother ice surface in subsequent measurements. In addition, from Fig. 2.3, where the ice surface at –4 °C and –15 °C is shown and how it changes over time, it can be seen that the boundaries of the crystals converge at warmer ice temperatures. Accordingly, at lower ice temperatures, it was observed that the ice surface becomes rougher after freezing. Although it was not possible to precisely define the changes in the ice surface in this experiment, visual observations justify the possible roughness of the ice surface. It is possible that the experimental method with forced motion (tribometers) could provide data, excluding the possible effects of vibrations. As the used experimental procedure is closer to real-life conditions, it is possible that the observed increase in vibrations due to environmental conditions is justified and its effect cannot be ruled out. Most likely, taking into account the literature [7], [15], similar relevances would be obtained by the forced experimental method.

3. SLIDING TIME PREDICTION MODEL AND METHODOLOGY

3.1. Relevance between environmental conditions and sliding time

In order to view the relevance between the measured and the predicted sliding time, using one parameter to describe the environmental conditions, the respective graphs were initially created (see Fig. 2.6). Equations obtained from the graphs using Microsoft Excel 2017 computer program characterize the relevance between a specific environmental parameter and the sliding time. The coefficient of determination R^2 was used to assess the closeness of relevances (see Table 3.1).

The measured sliding time and the sliding time calculated from relative air humidity, air temperature, and ice temperature using Equations (3.1)–(3.3), as well as absolute and percentage errors are shown in the full text of the Doctoral Thesis.

Table 3.1

Sliding time depending on humidity, temperature, and ice temperature

	Equation	R^2
Sliding time, depending on relative humidity	$T_{ks(RH)} = -1.4 \cdot 10^{-3} \cdot RH + 4.128$, (3.1.)	0.78
Sliding time, depending on air temperature	$T_{ks(gaiss)} = 0.7 \cdot 10^{-3} \cdot T_{gaiss}^2 - 6.9 \cdot 10^{-3} \cdot T_{gaiss} + 4.003$, (3.2.)	0.68
Sliding time, depending on ice temperature	$T_{ks(ledus)} = 3.7 \cdot 10^{-3} \cdot T_{ledus}^2 + 16.4 \cdot 10^{-3} \cdot T_{ledus} + 4.015$. (3.3.)	0.51

The results obtained indicate a mean percentage error of at least 0.20 % when one specific environmental parameter (in this case, relative humidity) is used to predict the sliding time. The highest mean percentage prediction error of 0.26 % and the highest error of 0.86 % were obtained when ice temperature was used for sliding time prediction.

3.2. Sliding time multifactor prediction model

For the development of the prediction model, measured independent related variables were used: relative humidity, air temperature, and ice temperature, and the resulting dependent variable – sliding time. The variables are summarized in Table 2.6 of the full version of the Thesis. When evaluating the obtained relevances between environmental conditions and sliding time, the relevance between air humidity is most closely described by the straight-line equation for air temperature and ice temperature – by the second-degree polynomial equation. The multiple regression equation was constructed, taking into account the observed trends. The model is still considered linear, although it contains nonlinear terms for independent variables because the regression coefficients are linear [45]. The multiple regression model was developed as follows:

$$T_{ks} = b_0 + b_1 T_{gaiss} + b_2 T_{ledus} + b_3 T_{gaiss} T_{ledus} + b_4 T_{gaiss}^2 + b_5 T_{ledus}^2 + b_6 RH, \quad (3.4)$$

where
$b_0, b_1 \dots b_n$ – regression coefficients;
RH – measured relative humidity, %;
T_{gaiss} – measured air temperature, °C;
T_{ledus} – measured ice temperature, °C.

Microsoft Excel Data Solver was used in this work, but other statistical programs, such as *MatLab*, *MiniTab*, etc. can also be successfully used to calculate regression coefficients $b_0; b_1; b_2; b_3; b_4; b_5; b_6$. In the computer program, the coefficients were calculated according to the least-squares method [45]. The obtained coefficients were placed in Formula (3.4):

$$T_{ks} = 4.064 + 4.1 \cdot 10^{-3} \cdot T_{gaiss} - 1.2 \cdot 10^{-2} \cdot T_{ledus} + 2.1 \cdot 10^{-3} \cdot T_{gaiss} \cdot T_{ledus} - 5.5 \cdot 10^{-5} \cdot T_{gaiss}^2 - 1.8 \cdot 10^{-3} \cdot T_{ledus}^2 - 9 \cdot 10^{-4} \cdot RH. \quad (3.5)$$

The obtained equation was checked for compliance. Pearson correlation coefficient *r*, which characterizes the degree of closeness of a linear relevance [45], [46], was calculated to be 0.94, indicating a close relevance between measured and calculated values. The obtained correlation coefficient was compared with the critical value $r_{\alpha;n}$ [46]. For 14 cases, the critical value $r_{\alpha;n}$ was read – 0.532. The correlation is plausible if $r_{\alpha;n} < r$.

To analyze the goodness-of-fit of the calculated values to the measured values, the adjusted coefficient of determination was used, where the number of independent variables and the number of measurements are taken into account [45]:

$$\bar{R}^2 = 1 - (1 - R^2)\frac{n-1}{n-p-1}, \quad (3.6)$$

where p is the number of independent variables and n is the number of cases.

Adjusted coefficient of determination $\bar{R}^2$ was obtained 0.80, indicating a close relevance between the calculated values and the measurement ones, i.e. 80 % of the measurements can be explained by the multiple regression model.

The regression model's standard deviation *(standard error of the regression)* shows the precision of the regression model – the lower the value obtained, the more accurate the regression model – 0.009. The standard deviation of the regression model is an absolute parameter that shows the average distance the data points are from the regression line [45]:

$$\sigma_{reg} = \frac{\sum_{i=1}^{n}(y_{apr.} - y_{izm.})^2}{n-p-1}, \quad (3.7)$$

where $y_{izm.}$ is experimentally measured sliding time values and $y_{apr.}$ is calculated sliding time values using regression analysis.

Using *Microsoft Excel Data Solver* software, the statistical significance of the empirical prediction model was assessed by analysis of variance *(ANOVA)*. According to Fisher's *F* test, if the Significance *F* for the regression equation does not reach 0.05 at a given level of significance (95 %), the developed regression model is statistically significant, or the data are reliable [45], [47], [48]. Significance *F* for the multifactor regression model was observed 0.004 (Appendix 6 in the full version of the Doctoral Thesis).

Table 3.2

The closeness of multifactor regression model relevances

Correlation coefficient r	Coefficient of determination R^2	The adjusted coefficient of determination $\bar{R}^2$	Standard deviation of the regression model σ_{reg}	Significance F
0.94	0.89	0.80	0.009	0.004

Using Formula (3.5), the sliding time was calculated (see Table 3.3). From the obtained data, it can be concluded that the average percentage prediction error using multifactor regression analysis is 40 % smaller than using the relevance between relative humidity and sliding time (0.20 % vs. 0.12 %).

Table 3.3

Comparison of the predicted sliding time with the measured one by multiple regression analysis

Experiment	Measured sliding time, s	Calculated sliding time, using (3.5), s	Δ Sliding time, s	Δ Sliding time, %	Experiment	Measured sliding time, s	Calculated sliding time, using (3.5), s	Δ Sliding time, s	Δ Sliding time, %
1	3.991	3.988	0.004	0.09	8	4.025	4.019	0.006	0.14
2	3.982	3.988	0.006	0.14	9	4.005	4.005	0.000	0.00
3	3.981	3.990	0.009	0.24	10	4.009	4.011	0.002	0.05
4	4.002	4.001	0.001	0.03	11	4.038	4.050	0.012	0.29
5	3.997	3.998	0.001	0.04	12	4.043	4.043	0.000	0.03
6	3.995	3.998	0.003	0.07	13	4.026	4.014	0.012	0.30
7	4.003	4.002	0.001	0.02	14	4.035	4.024	0.011	0.28
Mean error								0.005	0.12
Highest error								0.012	0.30

Regression coefficients were standardized to determine which environmental conditions parameters were more important in predicting the sliding time. Standardization of regression coefficients is used if the coefficients of one regression equation are not comparable. Using regression coefficient standardization, all variables are expressed as standard deviations from the arithmetic mean [49] :

$$\frac{x_1 - \overline{x_1}}{\sigma_1}; \frac{x_2 - \overline{x_2}}{\sigma_2}; \dots \frac{x_k - \overline{x_k}}{\sigma_k}. \quad (3.8)$$

As a result, the following regression equation was obtained:

$$T_{ks(stand)} = 2.2 \cdot 10^{-14} + 1 \cdot T_{gaiss(stand)} - 0.9 \cdot T_{ledus(stand)} + 1.3 \cdot T_{gaiss(stand)} \cdot T_{ledus(stand)} - 0.09 \cdot T^2_{gaiss(stand)} - 0.9 \cdot T^2_{ledus(stand)} - 0.6 \cdot RH_{(stand)}. \quad (3.9)$$

The regression coefficients (3.9) can be compared to get a general impression of the effect of the parameters (the higher the coefficient, the greater the effect). Humidity has the smallest effect (0.6), but it is not significantly lower than that of ice or air temperatures (0.9; 1). In this case, no specific parameter can be excluded from the regression equation. The obtained result indicates that all three environmental parameters are essential to explain the effect of environmental conditions on the sliding time.

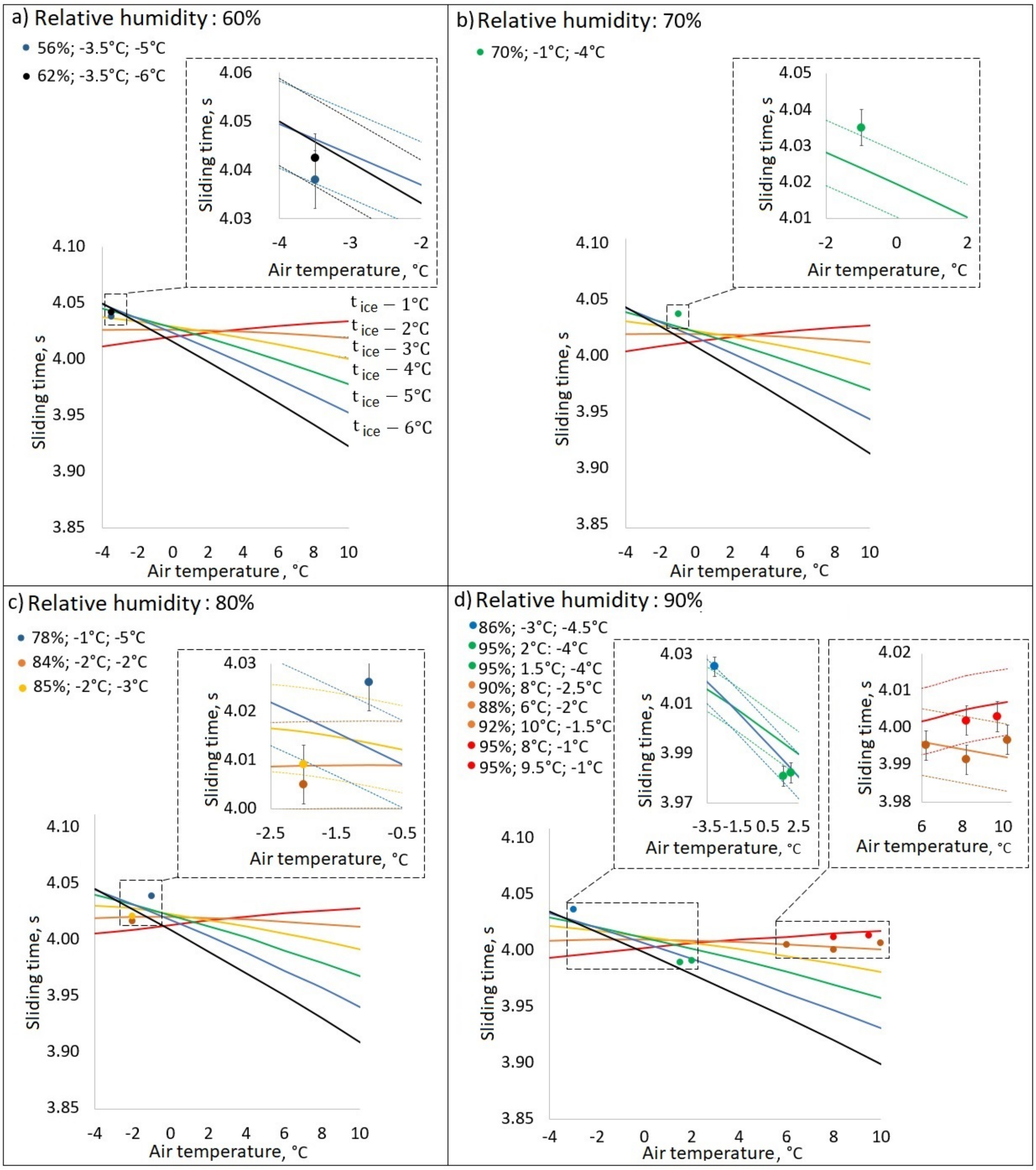

Fig. 3.1. Comparison of the calculated sliding time (curves) with the experimentally obtained sliding time (points); (a) relative humidity 60 %; (b) relative humidity 70 %; (c) relative humidity 80 %; (d) relative humidity 90 %. *The indicated theoretically calculated ice temperatures in a) correspond to b), c), d).*

To compare the experimental measurements with the calculated values, Fig. 3.1 is divided into four parts based on humidity (relative humidity from 60 % to 90 %). Using the prediction model (3.5), the theoretical sliding time curves were calculated at six ice temperatures (from –

1 °C to –6 °C) at the indicated relative humidity and air temperature range (from –4 °C to +10 °C). The measured experimental results (points in graphs) were analyzed according to the indicated environmental conditions. The dashed thin lines indicate the standard deviation limits of the regression model (±0.009).

From the date in Fig. 3.1, it can be concluded that the experimentally obtained sliding time results are within the standard deviations of the regression model and the standard deviation of the experimentally obtained data. This suggests that the theoretical model can be used to predict sliding parameters depending on environmental conditions. Although the experimentally obtained points within the standard deviation correspond to the calculated curve, some inaccuracies are observed (the green point at 70 % humidity; the blue point at 80 % humidity; green points at 90 % humidity). They can be explained by the fact that the theoretical curves are calculated at specific humidity but the experimental points are obtained under slightly different conditions.

Although the model allows predicting the result under any conditions, the fastest results (see Fig. 3.1) should be considered cautiously because the experiments did not have conditions with high air temperature and low ice temperature; thus claiming that such conditions ensure the lowest sliding time is not safe. To obtain reliable results, the environmental conditions must be within the following limits: ice temperature from –6 °C to –1 °C; air temperature from –4 °C to 10 °C; and air humidity from 60 % to 95 %. Inaccuracies can also occur if the air temperature is between 5 °C and 10 °C and the ice temperature is below –4 °C. The boundaries of the prediction model are based on the data of the performed experiments.

3.3. Development of sliding time measurement and prediction methodology

The developed methodology for measuring and predicting the parameters characterizing the friction pair stainless steel-ice sliding ability using on-field type experimental regime is presented in Appendix 11 of the Doctoral Thesis.

The measurement and prediction methodology is intended for measuring the sliding characteristic parameter – sliding time, s, as well as environmental conditions – relative air humidity, %, air temperature, °C, ice temperature, °C – and for the development of prediction model, which predicts sliding time according to environmental conditions, in on-field type experimental mode.

Experimental and theoretical research

In order to use the experimentally obtained data for the development of the prediction methodology, a sliding time measurement procedure was developed (see Section 2.6). In the development of the prediction methodology for parameter T_{ks} it is assumed that the experimental studies have been performed following the measurement procedure and the obtained results of sliding time measurements are in line with the set criteria.

After the performed experimental research, the obtained data is processed, the theoretical prediction model is developed and evaluated. Statistical methods were used in data processing; descriptive statistics and inferential statistical methods for determining correlations were used to develop the prediction model – multiple regression analysis and correlation analysis.

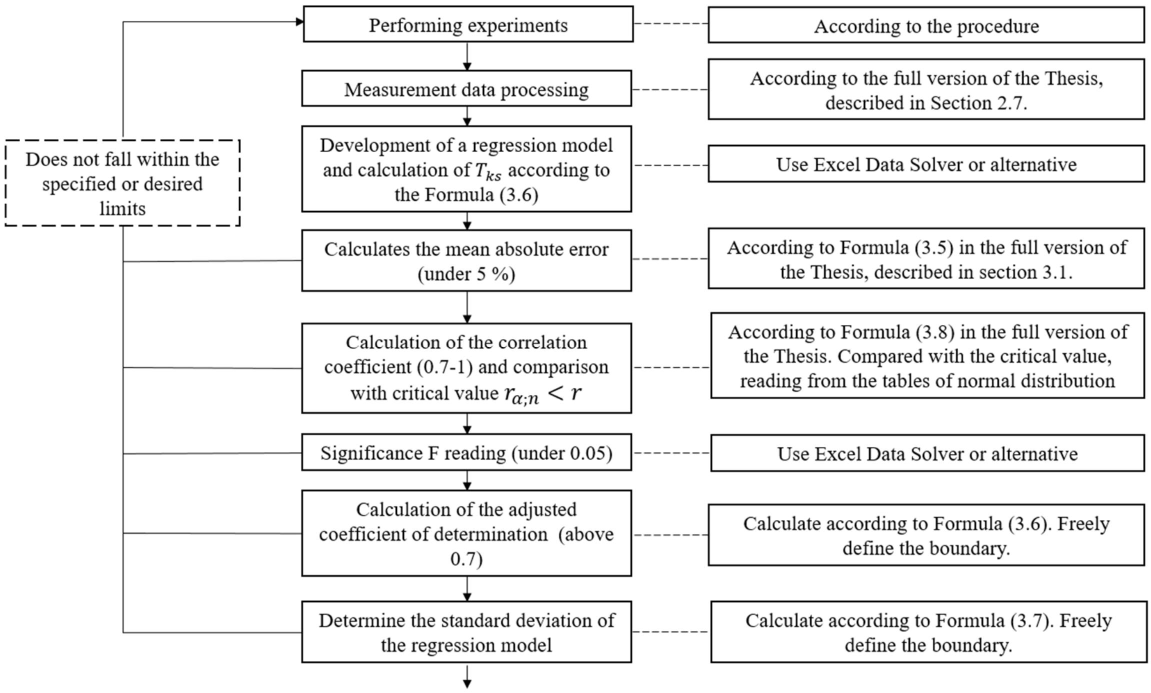

Fig. 3.2. Algorithm for prediction model development and evaluation.

The algorithm for calculating and evaluating the sliding time parameter T_{ks}, which characterizes the sliding of the sample on the ice depending on the environmental conditions (see Fig. 3.2), is as follows:

1. To calculate parameter T_{ks}, a multiple regression model is developed according to Formula (3.4). *Microsoft Excel Data Solver* is used to calculate regression coefficients $b_0; b_1; b_2; b_3; b_4; b_5; b_6$. Other statistical programs, such as *MatLab, MiniTab*, etc. can also be used successfully.
2. The calculated values are compared with the meters to calculate the mean absolute percentage error. Although in the known literature mean absolute percentage error below 10 % is considered with high approximation accuracy [50], since it directly depends on the value of the measured parameter, the limits of high approximation accuracy should be considered with some caution [51]. If the sliding time is measured according to the developed methodology, the author recommends reducing the average absolute percentage error limit at least two times.
3. For the general evaluation of the correlation, the correlation coefficient r (in the range from –1 to 1) is used primarily, which characterizes the degree of closeness of the linear relevance.
4. To make sure that the obtained correlation coefficient can be used to evaluate the dependence, it should be compared with the critical value $r_{\alpha;n}$ (read from the normal distribution tables, determining the critical value of the correlation coefficient, depending on the number of cases [56]). The correlation is plausible if $r_{\alpha;n} < r$.
5. Using the obtained analysis of variance, determine the Significance F of the multifactor regression model to assess whether the developed model is statistically significant (the result is not attributable to randomness). If Significance F is less than 0.05, the developed model is statistically significant.

6. The corrected coefficient of determination $\bar{R}^2$ is calculated according to Formula (3.6) to estimate the percentage of experimental measurements that the obtained theoretical prediction model can explain. The permissible value of the coefficient of determination (in the range from 0 to 1), which indicates, in a particular case, a close relevance, is not strictly defined in the known literature; therefore, the permissible limit can be freely chosen. The author believes that it should be greater than 0.7.
7. The standard deviation of the regression model, which shows the accuracy of the regression model analysis, is calculated according to Formula (3.7). The standard deviation of the regression model shows the average distance the data points are from the regression line. Also, in this case, a satisfactory standard deviation of the regression model is freely chosen.

Suppose any of the described steps does not meet the specified or desired requirements. In that case, additional experimental measurements are performed, preferably at other environmental conditions, following the described field type experiment procedure and a modified prediction model.

Methodology evaluation

The developed sliding time measurement and prediction methodology depending on the environmental parameters (air humidity, air and ice temperature) is based on experimental measurements describing in detail the sliding time measurement procedure in the on-field type experimental mode. The prediction parameter T_{ks}, which characterizes the sliding of the sample on the ice depending on the environmental conditions, is calculated using multiple regression analysis, and the regression model is evaluated.

The on-field type experimental mode methodology requires a sufficiently specific technical support, which can be modified as needed. In the full version of the Doctoral Thesis in Chapter 2.6 “The field type experiment procedure” the author describes the possibility to develop a device (patent application No. LVP2020000098) with the help of which similar types of experiments could be performed not only on the trestle, but also on a flat surface (for example, a hockey field). This would accordingly facilitate the experimental procedure and allow data to be collected at different sliding speeds. As a result, a more accurate theoretical model for predicting sliding parameters could be developed.

4. APPROBATION OF THE PREDICTION MODEL AND DIRECTIONS OF FURTHER RESEARCH

4.1. Approbation of the prediction model and comparison with the results of the skeleton competition

Practical approbation

The developed model for predicting the parameters characterizing the sliding ability was practically approbated in the training of the Latvian Skeleton team on the Sigulda bobsleigh and sleigh track and on the start training platform. The model was used to predict the sliding time depending on the environmental conditions, by changing the ice temperature and training on different days. Consequently, it was analyzed which skeleton runners should be used by athletes under specific environmental conditions. The letter of approbation is presented in Appendix 10 of the Doctoral Thesis.

Comparison with the results of skeleton competitions

A comparison was made to test how the friction pair stainless steel-ice sliding parameters that were obtained based on the regularities of environmental conditions (T_{ks}) correlate with the athletes' results in the *IBSF* World Cup skeleton competition.

Parameter T_{ks} was calculated according to Formula (3.5), depending on the environmental conditions during the competition. As a comparative result of the *IBSF* World Cup skeleton competition the average total sliding time of the 5th – 10th place in the 2nd run was chosen for both male and female athletes. The *IBSF* World Cup skeleton competition results were obtained from the last three stages of the Sigulda bobsleigh and skeleton competition track. Ice and air temperature values were taken from official measurements before the 2nd run. Accordingly, the relative humidity was determined from the values indicated at the meteorological observation station (see Table 4.1 for the values in the Thesis full version).

To compare the data, Fig. 4.1 was created, where the calculated value of T_{ks} is indicated on the x-axis and the average sliding time of positions 5–10 on the y-axis from the 2nd run: a) the results of women's competitions, b) the results of men's competitions. According to the data, a linear relevance can be observed between T_{ks} and the average sliding time of positions 510 in both women's and men's competitions, i.e., if the predicted sliding time parameter decreases, depending on environmental conditions T_{ks}, the average sliding time in competitions also decreases. The significantly lowest sliding time in the competition and the lowest T_{ks} were obtained on 27 November 2020 – men's competition day (environmental conditions: air humidity 90 %; air temperature 0.5 °C; and ice temperature –7 °C). This result indirectly indicates that the relatively significant difference between air and ice temperatures at high humidity provided a lower sliding time (lower coefficient of friction) and was in line with the trends of the developed prediction model.

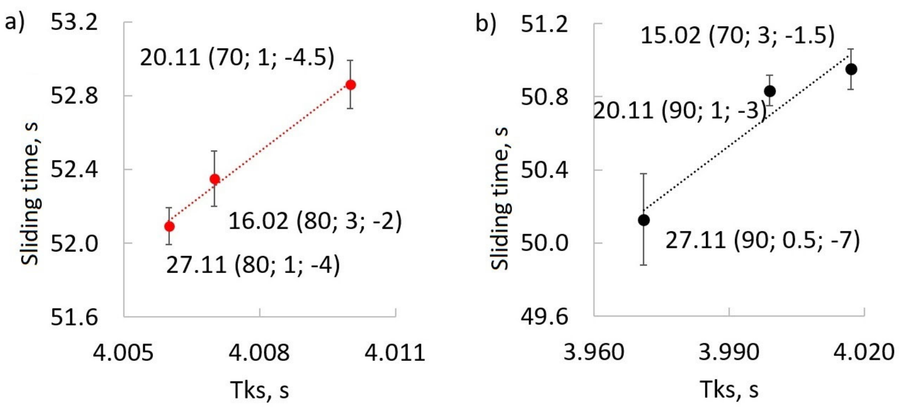

Fig. 4.1. The average sliding time versus T_{ks}: a) women's competition results; b) results of men's competitions. *The following information is added to the result points: date; in brackets – humidity, %, air temp., °C, ice temp., °C).*

The obtained results, comparing the sliding times presented by the athletes in the competition with the calculated parameter T_{ks}, are currently a partial confirmation that the developed prediction model can be successfully used to predict the sliding ability trends depending on environmental conditions also in real competition mode.

4.2. Influence of environmental conditions and surface roughness on the coefficient of friction in the laboratory

In order to get a general impression of the effect of changes of environmental conditions on another describing result (friction coefficient), experiments were carried out at *V Research GmbH (Industrial Research and Development), Austria*, within the framework of international mobility.

A linear tribometer *RVM 1000 (Austria)* with a freezing chamber was used for the research. Equipment of a similar type has been used in other studies [10], [12], [28], [29]; thus, it is possible to observe the trends that are likely to be repeated in the works of other authors. The dynamic coefficient of friction was measured with a tribometer as a descriptive parameter of sliding ability. As experimental samples, rectangular parallelepiped samples with dimensions – (35 mm × 18 mm × 14 mm) ± 0,1 mm were prepared. Mass of samples – 68 g ± 0.5 g. The samples were milled and ground from one workpiece: material – stainless steel *Uddeholm Ramax HH*. The work surface was polished with a *Mecatech 334 TI 15 (Presi, France)* automatic polisher, ensuring a surface roughness of *Sa* ~ 0.03 µm. To obtain different degrees of surface roughness, the samples were scratched with a cloth-based sandpaper of different grit sizes (400; 600; 1500 (*3M*)) parallel to the sliding direction of the sample [41] with a constant load of 10 N and a total distance of 2400 mm. As a result, four samples with the following surface roughness *Sa* ~ 0.02 were obtained (not scratched – polished sample), (0.07; 0.14; 0.22) µm. Roughness was measured with a Confocal microscope *VK–X250/260 (Keyence International NV/SA, Mechelen, Belgium)* for a 2 mm × 2 mm area. Measuring settings were in accordance with *EN ISO 4288* and *EN ISO 3274* [52], [53].

Before each series of experiments, the ice was prepared in a new, specially designed ice freezer (20 mm × 80 mm × 5 mm). The ice was frozen from the bottom of the freezer, obtaining the surface temperature of about –9 °C. Ice temperature was measured with a contact type thermometer *JUMO dTRANS T04 (JUMO, Germany*) and the air temperature and relative humidity with a *Dostmann electronic LOG 110–EXF (Dostmann electronic, Germany)* thermometer.

The experiments were performed under two environmental conditions (denoted by: "cold" and "warm"), at six different velocities (0.024–0.288 m/s), with four samples with different degrees of surface roughness (for more information, see the full version of the Doctoral Thesis). The method of the experiments is described in the [54]–[56]. The results described are included in [55]. In order to define the environmental conditions, parameter T_{ks} , obtained theoretically under such conditions, was calculated according to Formula (3.5). The percentage difference between environmental conditions was obtained ~ 2 %. In this case, T_{ks} is used only as an indicator to theoretically characterize the effect of environmental conditions on the sliding ablity of the sample on ice (higher T_{ks} corresponds to a longer sliding time and therefore, slower sliding on ice).

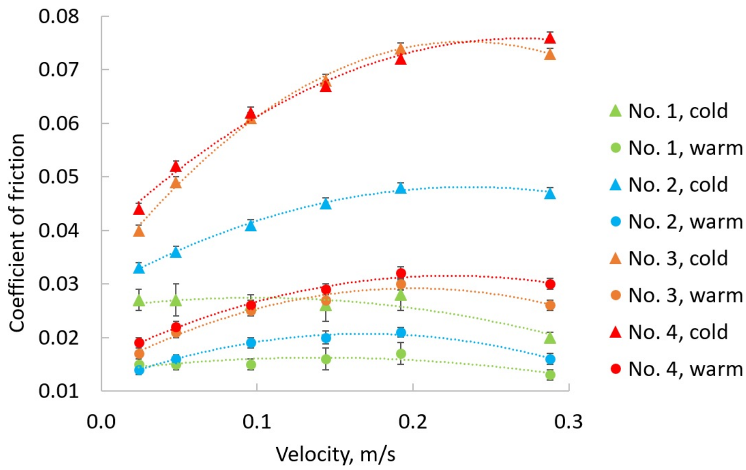

Fig. 4.2. Dynamic coefficient of friction values for samples: No. 1 (*Sa* ~ 0.02 µm), No. 2 (*Sa* ~ 0.07 µm), No. 3 (*Sa* ~0.14 µm), No. 4 (*Sa* ~0.22 µm), depending on environmental conditions ("cold" – air temperature ~3 °C, ice temperature ~ –9 °C, humidity ~20 %; "warm" – air temperature ~6 °C, ice temperature ~ –9 °C, humidity ~ 60 %.) and sliding speed.

The obtained data are represented in Fig. 4.2. Green color indicates Sample No. 1 (*Sa* ~ 0.02 µm), blue – Sample No. 2 (*Sa* ~ 0.07 µm), orange – Sample No. 3 (*Sa* ~ 0.14 µm), and red – Sample No. 4 (*Sa* ~ 0.22 µm). The triangle indicates measurements under "cold" conditions, the circle – measurements under "warm" conditions. According to the obtained data, it can be seen that the value of the coefficient of friction for all samples differs significantly (more than 2x) between two measurements of environmental conditions. In relation to the environmental conditions, this can be explained as follows, with a 2 % change in T_{ks} the effect on the coefficient of friction is 70 % for Sample No. 1, 129 % for Sample No. 2, 144 % for Sample No. 3, and 134 % for Sample No. 4. If the change in the coefficient of friction is similar for Samples No. 2 to No. 4, then for Sample No. 1, it is about two times smaller than for the others.

It is possible that for surfaces of experimental samples with lower surface roughness (polished), the influence of environmental conditions on the result is smaller than for the surfaces with higher surface roughness.

This observation was in line with that observed in Spagni's work [5], namely, three samples with different surface roughness (*Ra* ~ 0.1 µm; 1.4 µm; 2.6 µm) were tested and, with increasing roughness, the difference between the measured coefficient of friction at five different ice temperatures (from –2 °C to –17 °C) increased from ~0.007 for the smoothest sample to ~0.018 for the roughest sample. It is possible that for rougher samples, as the ice temperature increases, and thus the ice hardens, the surface roughness serves as a relative plow, which in contact with the ice surface promotes an increase in the coefficient of friction. For samples with less surface roughness, the height of roughness is lower; therefore, in contact with ice, no additional resistance occurs if the hardness of ice increases.

After experiments in the laboratory of *V–Research GmbH (Industrial Research and Development)*, it can be concluded that in the experiments where the coefficient of friction is measured, it is even more critical to fully define the environmental conditions. More information is presented in the full version of the Doctoral Thesis.

MAIN RESULTS AND CONCLUSIONS OF THE STUDY

1. After the analysis of the known literature it was concluded that the description of experimental conditions in the works of various researchers is insufficient. As a result, incomparable, chaotic results emerged. Given that primarily environmental conditions are described by ice temperature, less often by air temperature or humidity, these parameters were chosen to study the effect of environmental conditions on the sliding ability of the sample on ice.
2. The on-field type experimental procedures used so far are incomplete, which calls for questioning the quality of the obtained results. Therefore, an on-field type experimental procedure was developed, which eliminates the shortcomings of the previously known procedures.
3. From the empirically obtained correlations of each environmental parameter (relative humidity, ice temperature, and air temperature) with the sliding time, it was concluded that in order to explain the results, information on the three considered environmental parameters is needed. The sliding time decreases as the humidity increases; the ice temperature is ~ –4 °C, and the air temperature is ~ 0 °C to + 4 °C.
4. A sliding time prediction model was developed taking into account the interaction of three descriptive parameters of environmental conditions using multiple regression analysis (range of environmental conditions: air temperature from –4 °C to 10 °C; ice temperature from –6 °C to –1 °C; relative air mortality from 60 % to 95 %). The model was checked for compliance, finding that it was correctly designed. The mean percentage error of the prediction using the developed prediction model was calculated to be at least 40 % smaller than using one of the parameters describing the environmental conditions (relative humidity), which formed the closest relevance with the sliding time.
5. A methodology for measuring and forecasting the sliding time depending on environmental conditions was developed. The measurement and prediction methodology determines the measurement methods, requirements for measuring instruments, accessories, materials, requirements for operator qualification and safety requirements, requirements for measurement conditions and measurement procedures, processing of measurement results and accuracy control, requirements for measurement accuracy.
6. With the help of standardization of regression coefficients of the prediction model, it was obtained that all three parameters characterizing the environmental conditions used in the calculations have a significant effect on the sliding time.
7. According to the developed prediction model, it was obtained that to reduce the sliding time, there should be a high humidity (~ 90 %) and a significant temperature difference between the air and ice temperature. To confirm this result, experiments should be performed under laboratory conditions with the possibility of providing such conditions. The analysis of the results of skeleton competition indicated that such regularity exists because a significantly faster average sliding time was obtained under the following

environmental conditions: air humidity 90 %, air temperature 0.5 °C, and ice temperature –7 °C.

8. The influence of environmental conditions when measuring the dynamic coefficient of friction under laboratory conditions was observed even more significant than in the on-field type experimental mode. A 2 % change in environmental conditions (characterized by the sliding time parameter T_{ks} of the prediction model) results in at least a 70 % change in the value of the coefficient of friction.
9. The surface texture of the sliding sample (roughness range: *Sa* 0.03–0.12 µm) does not significantly affect the sliding time result in the on-field type experimental mode. Under laboratory conditions, the effect of surface texture (roughness range: *Sa* 0.02–0.22 µm) is significant and the values of the coefficient of friction can vary up to 4 times.

The obtained results indicate a significant impact of environmental conditions on the sliding between stainless steel and ice, as well as the need to describe the environmental conditions with more than one characteristic parameter. Therefore, it can be concluded that the proposed hypothesis – *"Air and ice temperature and air humidity interaction influence the sliding ability of friction pair stainless steel–ice. Knowing the influence of environmental parameters, it would be possible to predict the sliding ability charateristic parameters of friction pair stainless steel–ice depending on environmental conditions, as well as ensure the accuracy of measurements of sliding ability charateristic parameters and the reproducibility of the experiments."* – was confirmed in the Doctoral Thesis.

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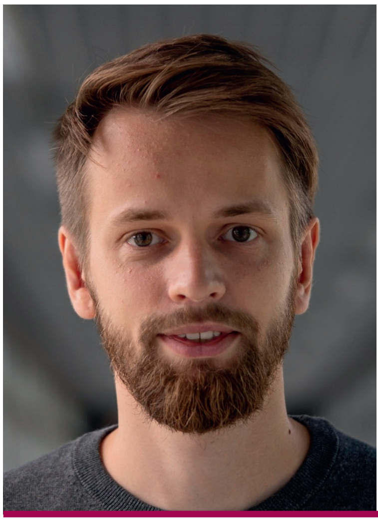

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