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Apparent Temperature Distribution on Scaffoldings during Construction Works

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***Abstract*—**People on construction scaffoldings work in dynamically changing, often unfavourable climate. Additionally, this kind of work is performed on low stiffness structures at high altitude, which increases the risk of accidents. It is therefore desirable to define the parameters of the work environment that contribute to increasing the construction worker occupational safety level. The aim of this article is to present how changes in microclimate parameters on scaffolding can impact the development of dangerous situations and accidents. For this purpose, indicators based on the human thermal balance were used. However, use of this model under construction conditions is often burdened by significant errors or even impossible to implement due to the lack of precise data. Thus, in the target model, the modified parameter was used – apparent environmental temperature. Apparent temperature in the proposed Scaffold Use Risk Assessment Model has been a perceived outdoor temperature, caused by the combined effects of air temperature, radiative temperature, relative humidity and wind speed (wind chill index, heat index). In the paper, correlations between component factors and apparent temperature for facade scaffolding with a width of 24.5 m and a height of 42.3 m, located at south-west side of building are presented. The distribution of factors on the scaffolding has been used to evaluate fitting of the microclimate model. The results of the studies indicate that observed ranges of apparent temperature on the scaffolds frequently results in a worker's inability to adapt. This leads to reduced concentration and increased fatigue, adversely affects health, and consequently increases the risk of dangerous situations and accidental injuries

***Keywords*—**Apparent temperature, health, safety work, scaffoldings.

I. INTRODUCTION

CONSTRUCTION works on scaffolding often cause dangerous situations and result in serious injuries. Workload and a wide range of external factors to which employees are exposed have a negative impact on their health. In 2015 there were 5776 accidents at work on construction sites in Poland, out of which 69 were fatal accidents and 84 were heavy ones [1]. Work related accidents most often are caused by numerous factors, as an incorrect psychophysical state of a worker. Studies show that improving the psychophysical condition of employees has the most significant impact on reducing the number of people injured in occupational accidents on construction sites [2]. The typical sufferers of occupational accidents on the construction site are employees aged between 20 and 29 [3]. Employee poor mental state could be caused by many factors, e.g.: sudden deterioration of a health condition, long, drawn-out or severe mental illness, consumption of alcohol or drugs as well as nervousness and fatigue, which may result from being in uncomfortable environmental conditions. The global warming as well as extended finishing works on the construction site often causes significant difficulties, due to extreme weather conditions, such as: high and sub-zero temperatures, strong wind or precipitation [4].

There are many methods of evaluating human thermal comfort in the external environment. The methods are divided into three main categories: thermal index, empirical index and indices based on linear equations [5].

Among many thermal indices could be specified:

- COMFA Model [6] – a mathematical model describing the human energy balance including perspiration rate, energy budget, core body and the skin temperature.
- PET (Physiologically Equivalent Temperature) based on the model of the energy balance for individuals MEMI (Munich Energy-Balance Model for Individuals) [7].
- SET (Standard Effective Temperature) defined as "equivalent temperature of the air in isothermal environment, with relative humidity of 50%, in which a person is dressed appropriately to the conditions and the type of activity, also has the same skin temperature and its humidity is as in real conditions" [8], [9].
- MENEX Model (Man Environmental Heat Exchange model) used for making an analysis of a human heat balance in the open area in in-situ and ex-situ conditions [10]
- UTCI (Universal Thermal Climate Index) one of the most modern indices, evaluating the human thermal load, defined as a reference air temperature, in which, in some defined environmental conditions, the basic physiological conditions of the organism take parameters as in real conditions [11].

Among indices based on linear equations are:

- H (Humidex) – presents wind chill - the temperature perceived by humans, which depends on the air temperature, apparent humidity and vapour pressure. Information about predicted values of Humidex are presented during weather forecasts in Canada, the United

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States of America and in the countries of Southern Europe. When the value of Humidex index is higher than 20 °C a special scale of thermal-humidity danger is used [12].

- HI (Heat Index)
- WCI (Wind Chill Index)
- The apparent temperature, determined by means of heat index and the wind chill index was used in this paper to present the environmental atmospheric changes, which are affecting the workers.

The article also presents a correlation between the component factors and the apparent temperature.

II. Thermal Indices

A. Heat Index

The Heat Index (HI) is an index which includes the air temperature and the apparent humidity. When the humidity is high, the water evaporation rate slows down and then the body holds a bigger amount of heat. One of the most basic tasks of the HI is to evaluate the thermal-humidity conditions. In order to do this, a scale of human thermal sensations is used. For the HI between:

- 27 and 32 °C, fatigue is possible after a longer exposure or physical activity,
- 32 and 41 °C, there can occur thermal contractions or thermal fatigue after longer exposure or physical activity,
- 41 and 54 °C, there is a danger of thermal contractions or thermal fatigue and a heat stroke is possible after longer exposure or physical activity.

For the HI above 54 °C there is a high risk of a heat stroke and muscle contractions after longer exposure or physical activity [13].

The equation of the HI is based on the apparent temperature (AT) suggested by Steadman [14] and on the multiple regression analysis including the influence of the temperature and the relative humidity presented by Rothfusz [15], in which the following dependencies, describing the HI, were presented:

$$HI = -8.784695 + 1.61139411\,T + 2.338549\,R - 0.14611605\,T\,R - 1.2308094 \times 10^{-2}\,T^2 - 1.6424828 \times 10^{-2}\,R^2 + 2.211732 \times 10^{-3}\,T^2 R + 7.2546 \times 10^{-4}\,T\,R^2 - 3.582 \times 10^{-6}\,T^2 R^2 \qquad (1)$$

where: T – ambient dry bulb temperature [°C], R - relative humidity [%]. This index is used by the National Oceanic and Atmospheric Administration (NOAA).

B. Wind Chill Index

Wind Chill Index (WCI) is an index which includes the air temperature and the wind speed, and is mostly applicable for evaluation of the climatic conditions, especially in winter time. This index was defined by Siple and Passel [16] on the basis of experiments conducted in Antarctica, in which heat losses from the surface of a copper cylinder were examined.

As a result of theoretical and experimental examinations conducted in Canada and in the United States of America a new winter time index has been created to evaluate the feeling of cold in humans – WCT (Wind Chill Temperature) and additional criteria were created to evaluate the biometeorological conditions. For the WCT at work [17] the following risks were listed:

- small risk of frostbites, discomfort and the risk of hypothermia during long period of time spent outdoors without proper clothing, for the temperature range from -27.9 °C to -10 °C,
- considerable risk of frostbites (frostbites possible after 10 – 30 minutes) and the risk of hypothermia during a long stay outdoors without proper clothing for the temperature range from -39.9 °C to -28 °C,
- high risk of frostbites (frostbites possible after 5 – 10 minutes) and the risk of hypothermia after a long stay outdoors without proper clothing for the temperature range from -47.9 °C to -40 °C.

For WCT lower than -55 °C there is an extreme risk of frostbites (frostbites possible after less than 2 minutes). Staying outdoors is dangerous to health and to life. This index is calculated according to [5]:

$$WCT = 13.12 + 0.6215 \times T - 11.37 \times V_{10}^{0.16} + 0.3965 \times T\,v_{10}^{0.16} \qquad (2)$$

where: T - the air temperature [°C], v_{10} - the wind speed at 10 m of height [km/h].

The WCT aggregates neither the influence of solar radiation nor worker clothing isolating parameters. It is applicable in cold climate with strong winds.

III. Examination of Scaffoldings at Construction Sites

Examination was done on a facade frame scaffolding at a construction site located in Warsaw, Poland. The scaffolding was examined between May 30 and June 3, 2016. The scaffolding was 24.5 m wide (ten modules), 42.32 meters high (20 levels of working decks) and the surface was 1036.84 m^2. The scaffolding was erected on the South West facade of a new office tower in construction (Fig. 1). The scaffolding was made out of elements from the BOSTA 70 system produced by Hunnebeck Company on the basis of a custom made project. In the scaffolding, the handrails and toe-boards were its security elements. Up to the twentieth level it was also cladded. Routine reviews of scaffolds were carried out every 10 days and after intense rainfalls or after rapid gusts of wind. The scaffolding has been used by max. three companies.

Occupational conditions on the scaffolding were monitored for one working week. Three rounds of tests were performed on each day: the first started from 8 a.m., the second from 11 a.m., the third from 3 p.m. Each measurement round lasted about one hour.

On the analysed scaffolding, the parameters were controlled on three levels – on the first level, eleventh level in the middle of the height and the highest scaffolding level. On each working deck there were four measurement points – two measurement points were in the extremes and two middle points were in the fourth and the seventh section. There was a total of twelve measurement points. Fig. 2 shows the diagram of the scaffolding with marked measuring points.

Fig. 1 A view of the scaffolding

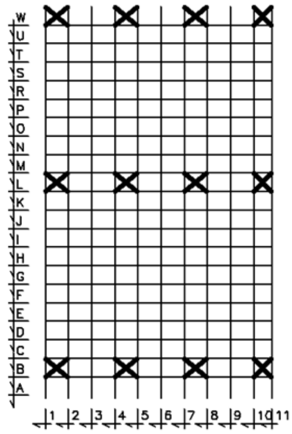


Fig. 2 Diagram of the Scaffolding

The scope of the complete research was very extensive and included measurements of: environmental parameters, such as – air temperature, relative humidity, atmospheric pressure, illumination, wind speed and direction, sound level, and dustiness (comp. [18], [19]), technical parameters – deviations from the ideal geometry of the scaffolding (imperfections), technical condition of the elements, forces in the anchoring, forces in the stand of scaffolding frame, frequency of vibrations, wind acting on the scaffolding structure, soil bearing capacity, operational loads (comp. [20], [21]) and physiological parameters of the workers (comp. [22]). The selected environmental parameters were used in this work to define the AT, i.e. air temperature, air humidity and wind speed.

IV. METHOD AND EQUIPMENT

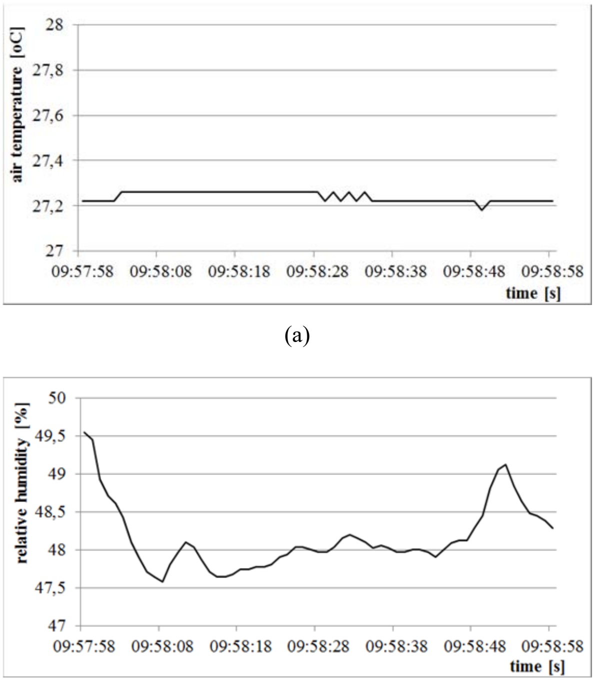
Measurements were made with the use of the KIMO AMI 310 multifunction device and the following probes (Fig. 3):

- atmospheric conditions module, measuring air temperature,
- vane probe (SHT 100) measuring wind speed.

In each measurement point, air temperature, atmospheric pressure, and relative humidity were measured at the height of the employee's face (about 1.5 m above the deck level). The duration of the measurement at each point was 4 minutes with a sampling period of 1 s. At the same time, wind speed was measured with the probe firstly directed perpendicularly to the scaffolding and next – along the scaffold façade (about 1.5 m above the deck level). Each measurement lasted for 1 minute and data were recorded at each second.

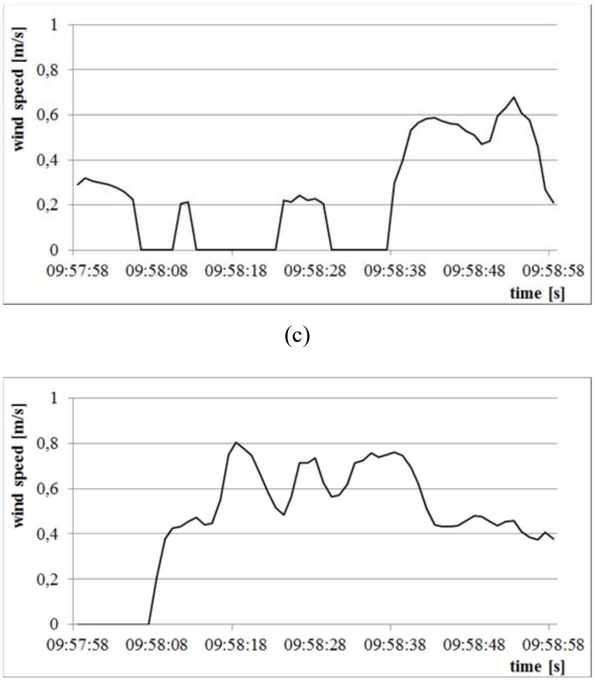
Fig. 3 The measurements on the scaffolding

In order to make a comparison (Fig. 4) there are values of air temperature, relative humidity and wind speed directed perpendicularly and parallel to the façade, which were measured on the scaffolding on the second day at 10 a.m. in the twelfth point.



(a)

(b)



(c)

(d)

Fig. 4 Sample time histories of: (a) air temperature, (b) relative humidity, (c) wind speed in the perpendicular direction, (d) wind speed in a parallel direction, measured at scaffolding W02

V. RESULTS

Tables I-III show the minimum, maximum and average values of air temperature, relative humidity and wind speed measured at the scaffoldings during five test days from 8 a.m., from 11 a.m. and from 3 p.m.

TABLE I
AIR TEMPERATURE

	Average temperature [ºC]	Minimum temperature [ºC]	Maximum temperature [ºC]
day 1, 11.00 a.m.	28.9	26.9	32.1
day 1, 3.00 p.m.	34.8	32.3	**37.2**
day 2, 8.00 a.m.	26.7	25.3	28.1
day 2, 11.00 a.m.	23.4	**21.4**	25.1
day 2, 3.00 p.m.	27.5	23.5	33.1
day 3, 8.00 a.m.	24.2	22.3	26.8
day 3, 11.00 a.m.	26.4	24.9	29.6
day 3, 3.00 p.m.	27.2	24.9	29.6
day 4, 8.00 a.m.	23.0	21.6	24.4
day 4, 11.00 a.m.	25.6	23.9	29.1
day 4, 3.00 p.m.	29.4	25.9	32.7
day 5, 8.00 a.m.	25.4	23.2	29.8
day 5, 11.00 a.m.	26.6	23.8	31.5
day 5, 3.00 p.m.	27.8	26.8	28.6

Measurements carried out at construction sites indicate that the air temperature, relative humidity and wind speed varied depending on the time of day [19], [23] and height [24].

Regarding the air temperature the maximum value, 37.2 ^{0}C, was observed on the first day in the measurement taken at 3 p.m., while the lowest value, 21.4 ^{0}C, on the second day in the measurement starting at 11.00 a.m. The maximum value of relative humidity, 79.9%, was observed during the second day of measurements starting at 11.00 a.m. (on this day there was also minimal temperature) while the lowest value during the first day in the measurement starting at 3.00 p.m. was 25.4% (there was a maximum temperature on this day). The maximum wind speed value, 10.4 m/s, was observed on the fourth day in the measurement starting at 11.00 a.m. (measured wind speed was directed perpendicularly to the facade).

TABLE II
RELATIVE HUMIDITY

	Average relative humidity [%]	Minimum relative humidity [%]	Maximum relative humidity [%]
day 1, 11.00 a.m.	41.2	33.5	58.7
day 1, 3.00 p.m.	28.6	**25.4**	34.8
day 2, 8.00 a.m.	48.9	43.4	69.1
day 2, 11.00 a.m.	68.0	61.8	**79.9**
day 2, 3.00 p.m.	50.9	36.8	64.6
day 3, 8.00 a.m.	60.4	49.4	71.6
day 3, 11.00 a.m.	52.4	43.5	78.0
day 3, 3.00 p.m.	48.1	42.2	78.0
day 4, 8.00 a.m.	63.0	57.4	68.6
day 4, 11.00 a.m.	45.9	34.0	55.0
day 4, 3.00 p.m.	33.5	27.5	38.8
day 5, 8.00 a.m.	38.0	29.5	58.4
day 5, 11.00 a.m.	33.9	25.4	43.4
day 5, 3.00 p.m.	30.7	28.6	33.5

TABLE III
WIND SPEED

	Average wind speed [m/s]	Minimum wind speed [m/s]	Maximum wind speed [m/s]
day 1, 11.00 a.m.	1.0	0	5.0
day 1, 3.00 p.m.	0.9	0	8.0
day 2, 8.00 a.m.	0.4	0	2.6
day 2, 11.00 a.m.	0.8	0	5.0
day 2, 3.00 p.m.	0.7	0	3.5
day 3, 8.00 a.m.	0.8	0	6.6
day 3, 11.00 a.m.	0.6	0	3.6
day 3, 3.00 p.m.	0.7	0	5.0
day 4, 8.00 a.m.	1.0	0	10.1
day 4, 11.00 a.m.	1.0	0	**10.4**
day 4, 3.00 p.m.	1.0	0	8.3
day 5, 8.00 a.m.	0.8	0	6.5
day 5, 11.00 a.m.	0.9	0	7.1
day 5, 3.00 p.m.	0.8	0	3.4

Since the temperatures measured on the scaffolding were higher than 20 ^{0}C, there is no need to present AT in the form of the WCT, the HI s enough. As a result, in Table IV HI is calculated on the basis of air temperature and relative humidity.

During five days in most cases the HI was between 27 ^{o}C and 32 ^{o}C. Work in such environmental conditions can lead to fatigue. In the evening on the first day the HI exceeded 32 ^{o}C and measured on average 34.2 ^{o}C, which means that people working on the scaffolding could have a heatstroke, experience muscles contractions and/or fatigue.

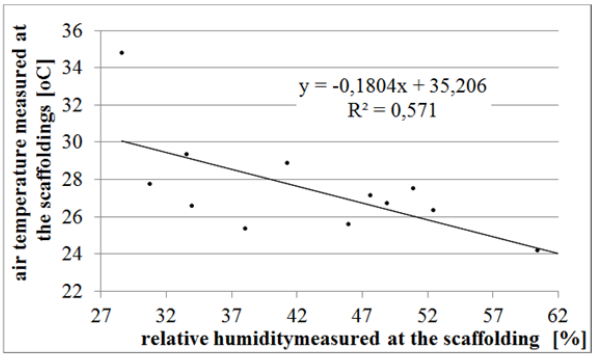
TABLE IV
HI

	Average HI [ºC]	Minimum HI [ºC]	Maximum HI [ºC]	Category
day 1, 11.00 a.m.	28.6	28.0	30.0	Caution
day 1, 3.00 p.m.	**34.2**	**32.6**	**36.7**	**Extreme caution**
day 2, 8.00 a.m.	27.1	26.8	27.6	Caution
day 2, 11.00 a.m.	24.6	24.5	24.8	
day 2, 3.00 p.m.	28.1	27.1	30.0	Caution
day 3, 8.00 a.m.	25.3	25.1	25.6	
day 3, 11.00 a.m.	27.0	26.6	27.7	Caution
day 3, 3.00 p.m.	27.4	27.1	28.2	Caution
day 4, 8.00 a.m.	24.6	24.6	24.7	
day 4, 11.00 a.m.	26.2	25.9	26.6	
day 4, 3.00 p.m.	28.5	27.8	29.6	Caution
day 5, 8.00 a.m.	26.0	25.5	26.8	
day 5, 11.00 a.m.	26.5	26.1	27.2	
day 5, 3.00 p.m.	27.0	26.7	27.3	Caution

Fig. 5 presents the dependencies between the factors measured on scaffoldings: air temperature, relative humidity, resultant wind speed. Resultant speed in each point has been calculated according to:

$$v_w = \sqrt{v_{\rightarrow}^2 + v_{\uparrow}^2} \tag{3}$$

where: $v_{\rightarrow}$ – wind speed directed parallel to the façade, $v_{\uparrow}$ - wind speed directed perpendicularly to the façade



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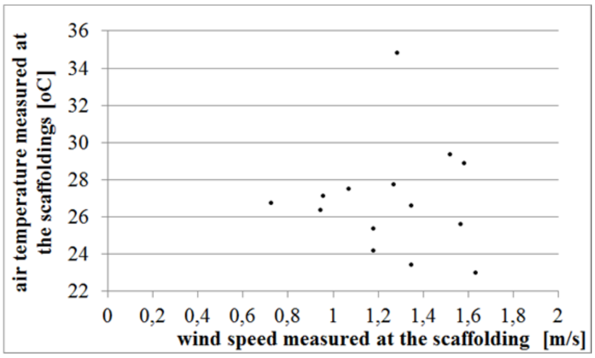

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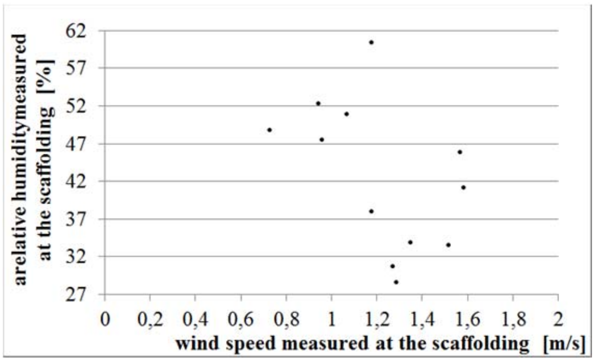
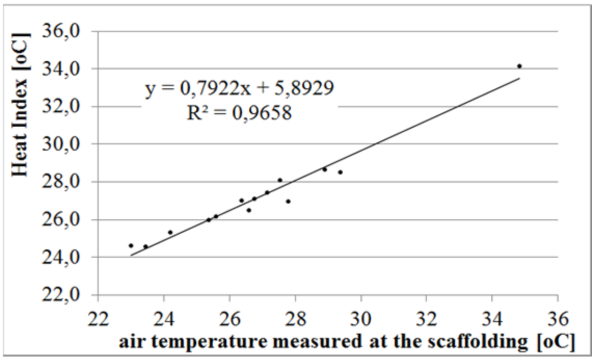


(c)

Fig. 5 The dependence of the values of (a) the air temperature and relative humidity, (b) the air temperature and wind speed (c) relative humidity and wind speed, measured at the scaffolding

Analysis of the obtained data shows weak dependencies between the air temperature and relative humidity. The air temperature lowers as the relative humidity rises. There is no correlation between the resultant speed, the temperature and humidity. It stems out of the fact that the wind speed on the scaffolding is influenced by other factors, especially those changing the flow.

Fig. 6 presents the dependency between the factors: air temperature, relative humidity, resultant wind speed and the HI.



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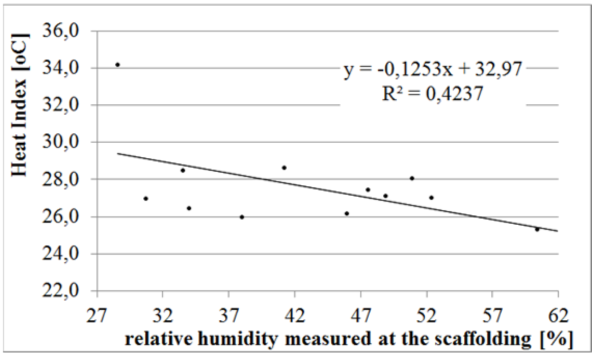

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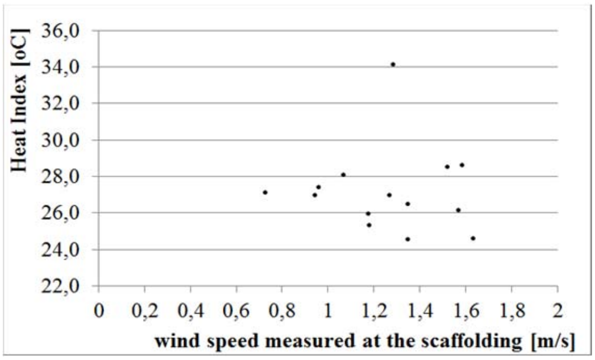

(c)

Fig. 6 The dependence of the values of (a) the HI and air temperature (b) the HI and relative humidity (c) the HI and wind speed, measured at the scaffolding

Because the HI is calculated on the basis of the temperature, humidity and wind speed, obviously there should be a correlation between these values and the HI. However, on the basis of the position of the points in Fig. 6, it can be proven that particular parameters affect the final value of the index. The analysis of the obtained data shows that the strongest correlation can be observed between the HI and the air, and the weakest correlation for the wind speed. It means that the temperature has the strongest effect on the value of the index and the wind has the lowest effect.

The HI increases linearly along the increase of the air temperature. The angular coefficient of approximating line dependences between the air temperature and the HI is lower than 1. This is related to the influence of the relative humidity. Weaker correlation is visible between the HI and the relative humidity.

VI. CONCLUSIONS

Unfavourable, dynamically changing environmental conditions are a heavy burden for people working outdoors. Work on scaffoldings is often performed on high altitudes where the climatic conditions are even more unfavourable. What is more, this work often requires physical exertion, increased focus and caution. For this reason, monitoring the environmental parameters of work is crucial.

The results show that the observed HI is often within ranges, in which there is a risk of occurring unfavourable physiological changes in people working at construction sites. It leads to reduced concentration, increased fatigue and poor mood. As a consequence, there is a higher risk of accidental injuries or dangerous situations which can lead to an accident. Additionally, the workers can be exposed to strong wind flows which can cause imbalance.

The paper presents test results valid for one scaffolding, which indicate the need to continue research as the presented results only indicate general dependencies. But, it cannot be a basis for qualitative evaluation of the relationship between the air temperature, relative humidity and the wind speed. Thus the studies of the occupational environment on scaffoldings should be continued to enable the development of a complex model.

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