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Application of infrared thermography in civil engineering: Limits and drawbacks

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ABSTRACT: Infrared thermography (IRT) is an effective diagnostic methodology for existing buildings monitoring, whose efficiency is however affected by the operator's technical knowledge. This paper presents experimental research aimed at evaluating the accuracy of IRT temperature measurements with respect to the incorrect setting of five input parameters required to be set by the operator: emissivity, reflected apparent temperature, ambient temperature, relative humidity, and distance. The goal was to highlight how their accurate evaluation and setting affects the thermographic survey and the post-processing stage. To this end, IRT experimental investigations were carried out on materials characterized by different emissivity and surface roughness, such as concrete, granite and steel. The experimentation outcome has pointed out the factors that most affect the temperature measurement error and allowed to quantify the error on the temperature measurements deriving from the incorrect setting of these parameters during the acquisition phase of the thermogram.

1 INTRODUCTION

Thermal controls represent the set of methods in which appropriate devices for the detection of heat are used to measure the temperature variation in physical components, structures, systems, or processes. Among the thermal control methods, Infrared Thermography (IRT) is a non-destructive investigation technique without physical contact with the inspected element based on the measurement of the electromagnetic energy radiated by the object in the infrared range of the electromagnetic spectrum. Infrared rays are related to heat as they originate from the emission of energy resulting from collisions between the molecules of the body because of their thermal agitation. All bodies having a temperature above absolute zero emit infrared radiations with increasing intensity as the body temperature increases due to the greater thermal energy radiated. Therefore, IRT remotely measures the thermal energy possessed by an object starting from the detection of the intensity of the infrared radiation emitted, allowing to trace back to the object surface temperature. Thanks to the amount of data that can be collected, the ease of inspection and the immediacy of the information, IRT used in the context of existing buildings diagnostics makes it possible to identify:

- thermal bridges,
- defects in thermal insulation,
- non-homogeneity of the walls,
- possible detachment of plasters or coatings,
- presence of humidity, condensation, water infiltrations,
- concealed systems,
- non-visible structural elements.

In addition, it is a supporting tool for:

- energy certification of buildings,
- investigations on historic buildings,
- diagnostics and restoration of decorated surfaces.

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The main tool of IRT investigations is the infrared camera or thermal camera, which detects the intensity of the infrared radiation emitted by the body and generates thermal maps or thermograms in chromatic scale representative of the distribution of temperatures in the scenario framed by the thermal camera, in which the hot spots, the cold ones and the heat gradients existing between the various parts of the examined surface are highlighted and quantified. In this way, a representation of the thermal gradients between different areas of the body and a model of the thermal distribution is obtained. However, thermal cameras observe the energy radiated by objects and not their temperature, therefore the temperatures are calculated indirectly by means of algorithms needing the setting of appropriate parameters - emissivity, reflected apparent temperature, ambient temperature, relative humidity, and distance - that the operator provides to the instrument in the phases preceding the measurement.

This paper reports an experimental work aimed at evaluating the accuracy of the temperature measurements, carried out by IRT, with respect to an incorrect setting of these parameters, to highlight how fundamental their accurate evaluation and setting is before running the thermographic survey and afterwards in the post-processing stage. To this end, IRT was carried out on specimens made of different materials, namely concrete, granite and steel, characterized by different physical characteristics.

2 INFRARED THERMOGRAPHY

The thermal camera not only detects the radiation emitted by the object, but also that which originates in the surrounding objects and reflected by the object itself. Both radiations vary according to atmospheric absorption, and the measurement can be strongly influenced by the ambient temperature. For a precise detection of the surface temperature of the object it is therefore necessary to consider these phenomena through appropriate algorithm and parameters that allow to account for the characteristics of the inspected elements and the operative environmental conditions, to correct the disturbance factors of the measurement. These parameters are the following.

- Emissivity ε of the object. Emissivity refers to the amount of thermal energy radiated by the object and expresses the ratio between the radiation emitted by the body at a given temperature and that emitted by the black body at the same temperature ($\varepsilon=1$); its values are therefore included in the range 0-1. A body with an emissivity close to 0 reflects all the incident energy, while if the emissivity is close to 1 the object has a behavior like the black body, tending to absorb all the incident energy without any reflection. The values included in the range 0-1 are typical of the so-called grey bodies, where part of the incident radiation is absorbed, and part reflected. The emissivity coefficient depends on the material, the surface conditions (roughness), the temperature and the wavelength.
- Reflected apparent temperature T_{rif}. The reflected environmental temperature permits to balance the radiation reflected by the object and that emitted from the atmosphere between the thermal camera sensor and the object itself. It is of fundamental importance to accurately set this value when the emissivity is low, the distance from the element under investigation is very high and its temperature is like that of the environment.
- Distance d between the object and the thermal camera. Setting this distance is important to balance the radiation absorption between the object and the thermal camera due to the transmittance, which decreases as the distance increases. When operating IRT, it is necessary to consider the presence of a medium between the source and the detector, represented in general by the atmosphere, whose gases have thermal properties as well, which need to be considered to avoid excessive attenuation of the radiation emitted by the object.
- Atmospheric temperature T_{atm}. It affects the thermal properties of the environment and the object.
- Relative humidity RH%. Relative humidity affects the transmittance to a certain extent. However, for short distances between object and detector and for standard humidity a default value of 50% can be used without excessive error.

The radiation recorded by the thermal camera is converted into an electronic signal which is then processed by specific software to produce digital images and map the distribution of surface temperatures through analytical calculations. The thermal camera's own processing algorithm operates based on a mathematical model according to a relationship of the type:

$$T = f(\varepsilon, T_{rif,} d, T_{atm,} RH\%) \tag{1}$$

IRT efficiency is therefore conditioned by the operator's technical knowledge and his ability to recognize and interpret the phenomena taking place around the object at the time of acquisition of the thermograms, as thermal cameras typically require the operator to set the five input parameters previously mentioned. Since the relationship (1) is highly non-linear, to evaluate the specific influence of the input parameters, in this paper the error was studied as a function of each individual parameter. It's worth underlying that the thermograms can be revised afterwards by previously mentioned post-processing codes, but information about real-time environmental conditions is needed and are to be recorded in situ. Another parameter which influences thermograms is surface roughness. In fact, the surface characteristics of the object are decisive for measuring the temperature by means of IRT. Depending on the surface condition, the degree of roughness and the type of coating, the emissivity changes. Smooth, shiny, mirror and/or polished surfaces usually have lower emissivity than matt, textured, rough, broken and/or scratched surfaces. The influence of surface roughness has been also investigated in this paper.

3 MATERIALS AND METHODS

3.1 *Materials*

IRT has been applied on specimens made of different building materials having different emissivity and with different surface roughness, as specified in Table 1. Specimens are also shown in Figure 1.

Table 1. Specimens' properties.

Material	Size (mm)	Roughness	Emissivity
Concrete	150x150	low	0.95
Concrete	150x150	high	0.95
Granite	120x200	low	0.80
Granite	120x110	high	0.77
Steel	50x80	low	0.35
Galvanized steel	50x80	high	0.27

3.2 *Methods*

IRT has been carried out using a high-resolution thermal camera SC660 R&D by FLIR Systems (Figure 2a).

Atmospheric temperature T_{atm} and Relative humidity RH% have been measured using a themo-hygrometer MENGSHEN M350 (Figure 2b).

Emissivity ε and Reflected apparent temperature T_{rif} have been determined according to the procedures specified in standard ISO 18434-1:2008 Part 1, Annex A.2 and A.1 respectively.

To avoid interferences, during IRT running the specimens were housed in a structure specially made for shielding the rays reflected from other bodies (Figure 2c).

The Distance d between the specimen and the thermal camera has been set at 1m.

The active IRT has been carried out heating the specimens with two 400 W halogen lamps.

Having completed the preliminary operations and having introduced the input parameters into the thermal camera, the indirect measurement of the temperature has been carried out, acquiring the thermograms relating to the specimen at regular object temperature intervals, and subsequently proceeding to their post processing by means of the supplied software of the thermal camera.

To evaluate the influence on the temperature returned by the thermograms of the error committed in setting the input parameters of the thermal camera, sensitivity analyses have been conducted, consisting in analysing the deviation of the temperature returned by the

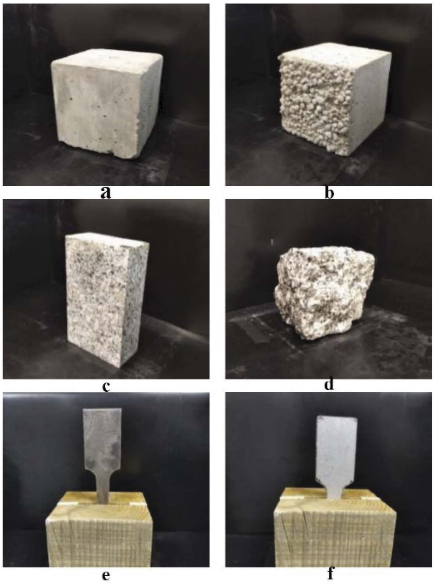

Figure 1. Specimen type. Concrete – low roughness (a), Concrete – high roughness (b), Granite – low roughness (c), Granite – high roughness (d), Steel – low roughness (e), Galvanized steel – high roughness (f).

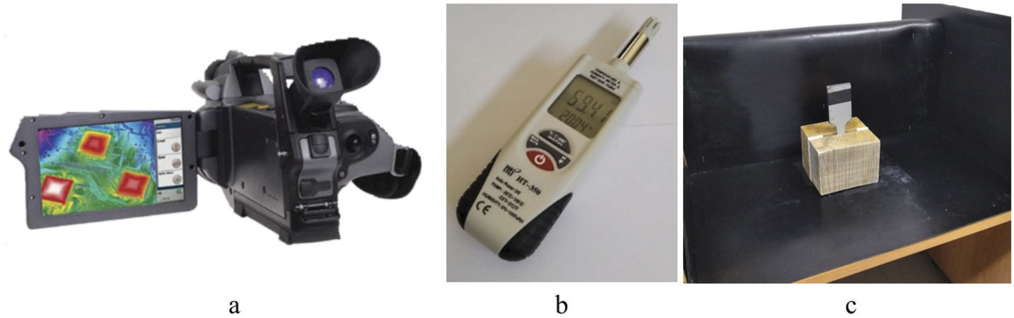

Figure 2. Instrumental set. Thermal camera (a), Thermohygrometer (b), Shielding structure (c).

thermogram with respect to the exact temperature measured with a contact thermometer, by varying a single input parameter at a time. The variation of each input parameter has been established within a range that simulated real operating conditions.

4 RESULTS AND DISCUSSION

4.1 *Sensitivity analysis. Emissivity*

Figure 3 shows the percentage deviation δT_{IRT} of the temperature returned by the thermogram with respect to the temperature T_{exact} measured with the contact thermometer as a function of the percentage emissivity deviation $\delta\varepsilon$ with respect to the correct value ε_{exact} for the concrete specimen with low surface roughness. The latter has been determined according to the procedure recalled in ISO 18434-1 Part 1, Annex A.2, at different temperatures. The terms involved in the subsequent diagrams are defined in Equations 1 and 2 as follows:

$$\delta T_{IRT} = \frac{T_{IRT} - T_{exact}}{T_{exact}} \cdot 100 \tag{2}$$

$$\delta \in = \frac{\varepsilon - \varepsilon_{\text{exact}}}{\varepsilon_{\text{exact}}} \cdot 100 \tag{3}$$

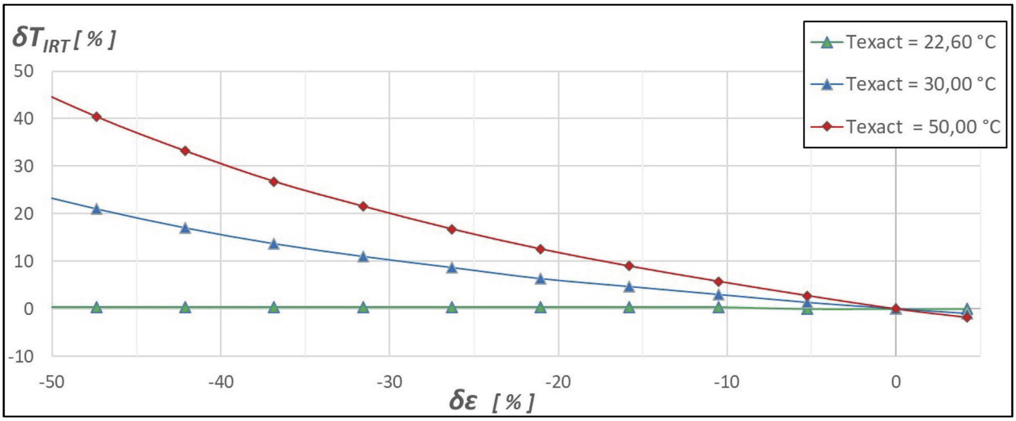

Figure 3. Influence on the temperature T_{IRT} returned by the thermograms of the error δε committed in setting the emissivity for the concrete specimen with low surface roughness.

With the same parameters meaning defined above, Figure 4 shows the deviation δT_{IRT} of the temperature returned by the thermogram with respect to the temperature T_{exact} as a function of the emissivity variation δε for the granite specimen with low surface roughness.

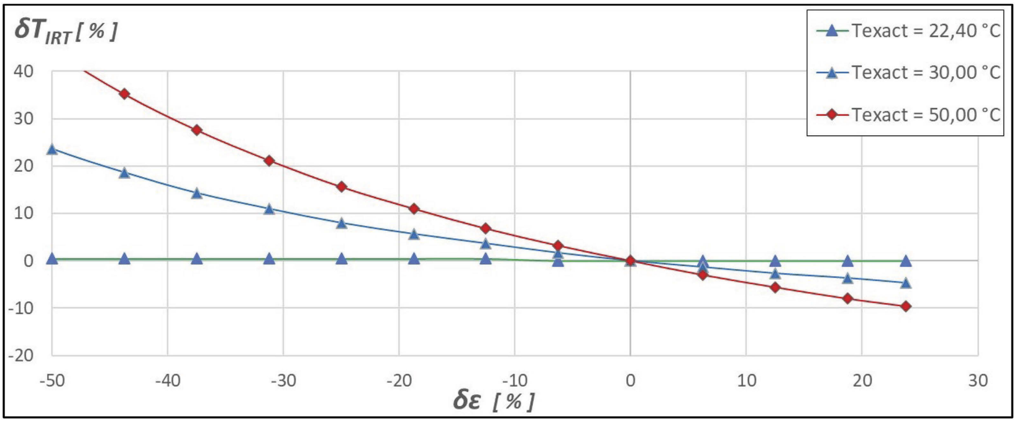

Figure 4. Influence on the temperature T_{IRT} returned by the thermograms of the error δε committed in setting the emissivity for the granite specimen with low surface roughness.

Figure 5 shows the deviation δT_{IRT} of the temperature returned by the thermogram with respect to the temperature T_{exact} as a function of the emissivity variation δε for the steel specimen with low surface roughness.

A summary of the errors according to the type of material and surface roughness is shown in Table 2.

4.2 *Sensitivity analysis. Reflected temperature*

Figure 6 shows the deviation δT_{IRT} of the temperature returned by the thermogram with respect to the temperature T_{exact} measured with a thermometer as a function of the reflected apparent temperature deviation δT_{rif} with respect to the exact value $T_{rif,exact}$, for the

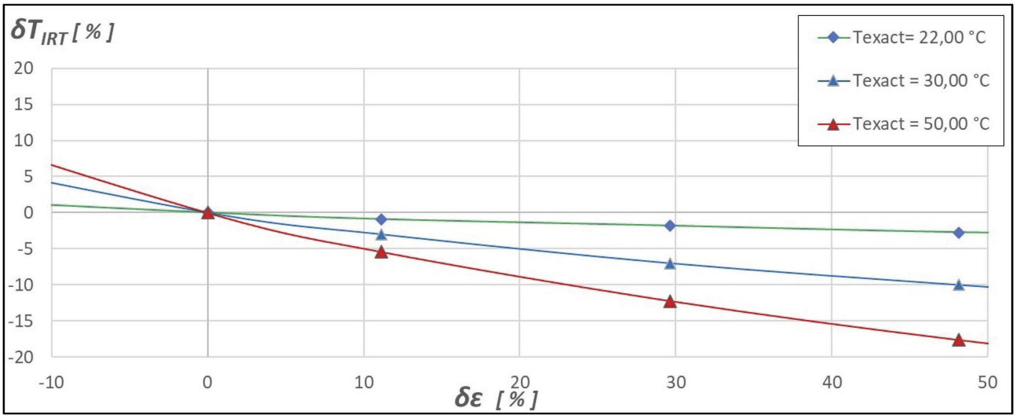

Figure 5. Influence on the temperature T_{IRT} returned by the thermograms of the error δε committed in setting the emissivity for the steel specimen with low surface roughness.

Table 2. Deviation δT_{IRT} with respect to T_{exact} as a function of material and surface roughness.

	Concrete	Granite	Steel
LR*	up to +45%	up to +120%	up to-38%
HR**	up to +140%	up to +110%	up to-42%

*Low Roughness, **High Roughness.

galvanized steel specimen with high surface roughness, defined as follows in Equation 4, the latter being determined according to the procedure recalled in ISO 18434-1 Part 1, Annex A.1, making use of a reflector made of a crumpled alluminium foil:

$$\delta T_{rif} = \frac{T_{rif} - T_{rif,exact}}{T_{rif,exact}} \cdot 100 \tag{4}$$

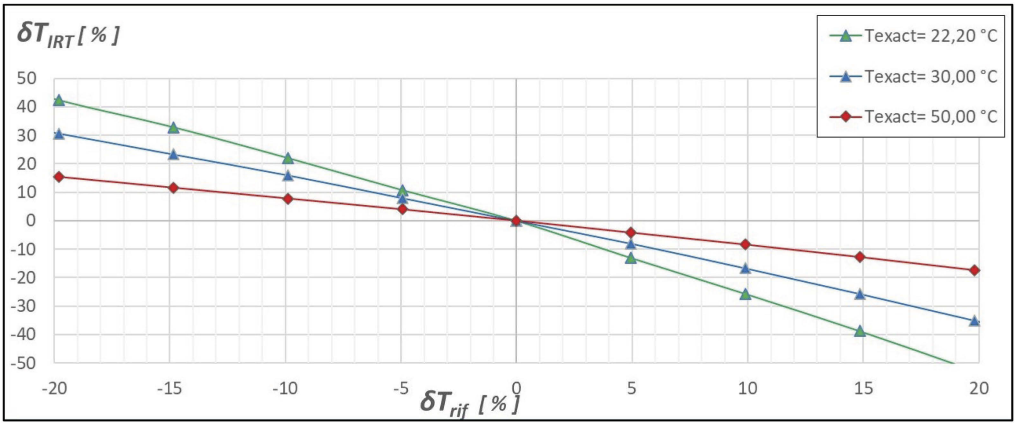

Figure 6. Influence on the temperature T_{IRT} returned by the thermograms of the error δT_{rif} committed in setting the reflected temperature for the steel specimen with high surface roughness.

A summary of the errors according to the type of material and surface roughness is shown in Table 3.

Table 3. Deviation δT_{IRT} with respect to T_{exact} as a function of material and surface roughness.

	Concrete	Granite	Steel
LR*	±2%	±9%	-80% +60%
HR**	±2%	±10%	-110% +90%

*Low Roughness, **High Roughness.

4.3 *Sensitivity analysis. Atmospheric temperature, relative humidity, and distance*

Table 4 summarizes the deviation δT_{IRT} of the temperature returned by the thermogram with respect to the temperature T_{exact} measured with a thermometer as a function of the Atmospheric temperature T_{atm}, the Relative humidity RH%, and the Distance d.

Table 4. Deviation δT_{IRT} with respect to T_{exact} as a function of material and surface roughness determined for T_{atm}, RH%, and d variation.

	Concrete		Granite		Steel	
	LR*	HR**	LR*	HR**	LR*	HR**
T_{atm}	0.2%+0.4%	0.3%+0.4%	0.4%+0.4%	0.4%+0.4%	0.9%+0.5%	1%+0.9%
RH%	0.2%+0.3%	0.3%+0.2%	0.3%+0.2%	0.2%+0.3%	0.4%+0.2%	0.3%+0.3%
d	+3%	+3%	+3%	+3%	+3%	+3%

*Low Roughness, **High Roughness.

4.4 *Discussion*

The results of the tests carried out on materials with different emissivity and surface roughness show that the input parameters that most influence the error of temperature measurement via IRT are the emissivity ε of the object and the reflected apparent temperature T_{rif}, while the other parameters, i.e., atmospheric temperature, relative humidity, and distance, have a less significant, even negligible, influence.

The results also highlight that the roughness of the surfaces can significantly affect the correct value of the temperature measurement, especially in the case of concrete and steel, since they affect remarkably the emissivity.

For all materials examined, the incidence of emissivity deviation increases with increasing temperature difference between the object and the environment, while the incidence of reflected temperature increases with decreasing temperature difference.

The influence of the latter error component increases significantly the more the material has a reduced emissivity, and therefore a high reflectivity, such as steel.

The results point out that the incorrect setting of emissivity has a strong impact on the accuracy of the temperature measurement. Since the thermal camera allows the user to set a single emissivity value for each object falling into its focus range at the time of acquisition of the thermogram, it is essential to identify the different emissivity of each framed object. In this regard, it is useful to examine Tables 5, 6 and 7, which report the entity of the possible errors in the case of material with high emissivity such as concrete (Table 5), medium-high emissivity such as granite (Table 6), low emissivity such as steel (Table 7).

Table 5. Error of T_{IRT} measurement as a function of incorrect setting of ε for concrete. T_{atm} = 20°C.

ε = 0.95 (correct value)		T_{exact} = 30°C	T_{exact} = 50°C
ε = 0.65	δε = 30%	δT_{IRT} = 11%	δT_{IRT} = 22%
ε = 0.50	δε= 48%	δT_{IRT} = 21%	δT_{IRT} = 40%
ε = 0.30	δε= 68%	δT_{IRT} = 48%	δT_{IRT} = 89%

Table 6. Error of T_{IRT} measurement as a function of incorrect setting of ε for granite. T_{atm} = 20°C.

ε = 0.80 (correct value)		T_{exact} = 30°C	T_{exact} = 50°C
ε = 0.55	δε = 30%	δT_{IRT} = 11%	δT_{IRT} = 21%
ε = 0.40	δε = 50%	δT_{IRT} = 24%	δT_{IRT} = 45%
ε = 0.30	δε = 62%	δT_{IRT} = 39%	δT_{IRT} = 71%

Table 7. Error of T_{IRT} measurement as a function of incorrect setting of ε for steel. T_{atm} = 20°C.

ε = 0.27 (correct value)		T_{exact} = 30°C	T_{exact} = 50°C
ε = 0.35	δε = 30%	δT_{IRT} = 7%	δT_{IRT} = 12%
ε = 0.40	δε = 48%	δT_{IRT} = 10%	δT_{IRT} = 18%
ε = 0.95	δε = 250%	δT_{IRT} = 23%	δT_{IRT} = 40%

It is interesting to note that if for concrete (Table 5) or granite (Table 6) the emissivity of steel is accidentally set (ε=0.30) a temperature measurement error of up to 70% can be made. Similarly, if for steel (Table 7) the emissivity of concrete (ε=0.95) is accidentally set, a temperature measurement error of up to 40% can be made. With this respect, it is worth noticing that, even though in post-processing codes it is usually possible to set different values of emissivity or reflected apparent temperature on different areas of thermograms, while carrying out an in-situ survey, the contemporary presence of different materials on the frame can be a critical issue, since the distribution of temperatures and consequent observations can be seriously affected. Therefore, when thermography is employed for in situ investigations aimed at real-time searching for structural anomalies or criticalities, attention need to be paid to a proper setting of the parameters.

5 CONCLUSIONS

This paper analyzed the influence on the temperature measurement via IRT of the incorrect setting of the input parameters that the operator must set in the thermal camera before the test, i.e. the emissivity of the object, the reflected apparent temperature, the atmospheric temperature, the relative humidity and the distance between the camera and the object.

The tests were carried out on samples of building materials with different emissivity and different surface roughness.

The results showed that the most influential parameters on the error are the emissivity and the reflected temperature, and that this influence generally increases as the surface roughness increases.

The operator must therefore be able to set these parameters correctly to avoid significant measurement errors which would distort the results of the IRT test and affect the temperature gradients in the thermograms to an extent that the structural anomalies or damage searched for in civil engineering surveys could be indetectable.

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