Understanding the Practical Problems with the Calculation of Surface Temperature

FESI document 5

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Executive Summary

This paper seeks to show that when installing thermal insulation systems it cannot be recommended to warrant the surface temperatures.

In reality, the assumed relation between the surface temperature and the thermal insulation value of an insulation system does not exist. The surface temperature does not give an indication of the heat loss. It is dependent upon a number of physical parameters which cannot be calculated or estimated with the necessary degree of certainty.

Where the contractor has no choice but to provide a warranty, then it is suggested that a large amount of qualification be made, listing the range of assumptions made to simplify the reality back to theory. Clearly with these assumptions in place, then actual temperature measurement is rendered meaningless.

1. Parameters influencing the surface temperature

1.1 The surface temperature of an insulation system is dependent upon a number of parameters, some of which are within the insulation system and some outside of the insulated surface.

1.2 Within the insulation system, parameters include:
- the hot-face temperature,
- the coefficient of thermal resistance of the insulation (lambda value) which is affected locally by any insulation and/or spacer-ring cladding supports and its moisture content,
- the surface coefficient of heat transfer at the surface of the insulation, which is made up of the combination of the heat transfer by convection and thermal radiation,
- the lateral thermal conductance in the cladding, which governs the reduction of local temperature peaks,
- the configuration of pipework whether horizontal or vertical, which is not always known at the pre-contract award stage when the contractor must make the calculations.

1.3 In addition, parameters such as thermal bridging and locally different heat transfer conditions, result in local differences in the surface temperature.

1.4 Outside the insulation surface, parameters include:
- the temperature of ambient air,
- wind speed and direction,
- solar radiation,
- radiation exchange with the colder night sky,
- radiation exchange with warmer and cooler surfaces coming from plant and equipment close by.
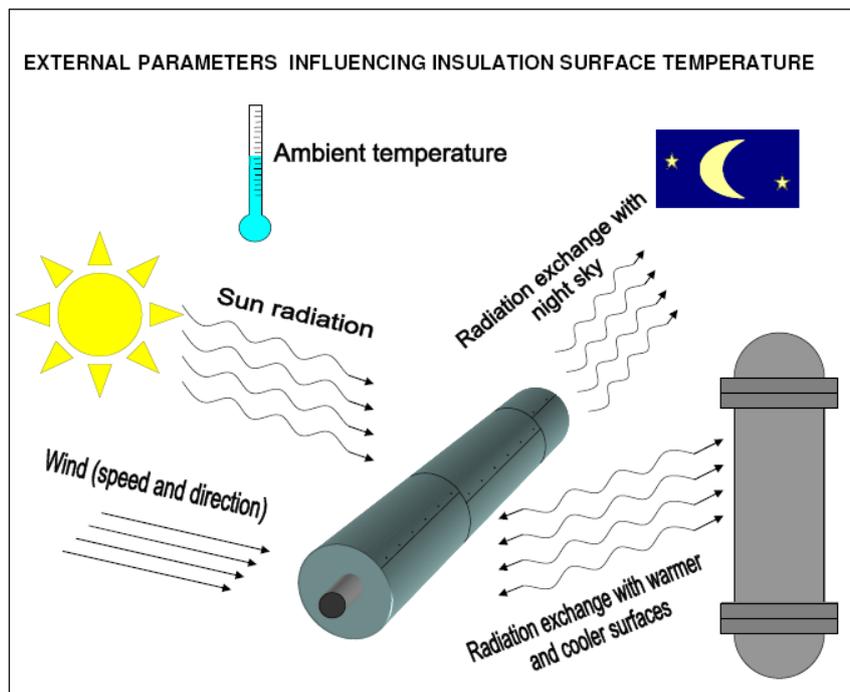
Figure 1:   External parameters influencing insulation surface temperature

1.5 It depends totally upon the level of knowledge of the insulated installation and its surroundings as to whether the parameters mentioned in 1.4 can be established with enough precision to ensure the compliance with a given surface temperature. When insulating an existing installation, these parameters should be easier to establish than a new build.

1.6 These parameters are outside of the sphere of influence of the insulation contractor, and so the designers cannot normally forecast these accurately enough to provide a basis for pre-contract award calculation. Therefore the designer should specify the values of these parameters, to be assumed for the basis of the pre-contract award calculation.

1.7 Taking into account all of the parameters mentioned above, excessive safety factors will need to be allowed to warrant a surface temperature. These safety factors will result in uneconomical insulation thicknesses.

1.8 It is important to note that differentiation should be made between thermal insulation for above or below ambient services. Especially in installations with a high hot-face temperature, the uncertainties caused by high thermal radiation by uninsulated components or local peaks in the ambient temperature where pipes run closely packed, are much greater than with cold insulation. In addition, temperature peaks in hot insulation as a result of heat conduction through metallic insulation and cladding supports, do not exist in cold insulation.

1.9 Practical experience has shown that with cold insulation, provided exact knowledge of the installation is known and where there is careful design of the insulation system, then it is possible to allow for the warranty of the prevention of condensation with an economically viable solution up to a relative humidity in the ambient air of less than 85%. **With thermal installations, however, the conditions are frequently so disadvantageous that the compliance with a specified surface temperature cannot be warranted.**

2. Calculation of surface temperature – the problem

2.1 This FESI document is intended to provide a serious warning to those who wish to, or are required to, predict the surface temperature of an insulated system. It highlights the problems associated with carrying out theoretical thermal and heat loss calculations and attempting to warrant surface temperatures. It will throw light on the complex considerations that are required when calculating the surface temperature of an insulated item. It particularly focuses on the risks of providing warranty for surface temperature based only on the commonly known parameters such as temperature of medium, ambient temperature and lambda value of the insulation material.

2.2 The document is aimed at persons trying to understand and document the problems of using a theoretical calculation of surface temperatures on insulated items.

2.3 While this document is primarily considering the impacts and implications to pipework, plant and equipment operating at temperatures above ambient temperature, it is still relevant to below ambient services.

2.4 In order to substantiate a calculated surface temperature, it must be measured once the installation is in service. This seemingly simple task is actually fraught with difficulty to achieve the accuracy required, particularly if a successful warranty depends upon it. Infra-red thermography is often the method used. Extreme caution is counselled and the problems of using this technique are discussed later.

2.5 The requirements for the thermal insulation of pipes, vessels and equipment are increasingly defined by performance specification. The specifier will state a required limiting maximum heat loss or gain together with a maximum surface temperature over the outside of the cladding or coating covering the insulation.

2.6 With these two requirements being stated together, it could be inferred that they are closely related and interdependent. This is not the case. While heat loss/gain and surface temperature are calculated from the same basic mathematical formulae, the requirements to regulate these two parameters are not the same. While heat loss/gain can be theoretically calculated with some degree of accuracy, the same cannot be said for surface temperature. This FESI document sets out to explain exactly why this is the case.

2.7 Some typical examples seen in specifications are:
'The insulation must be so designed that the surface temperature of the cladding will not exceed 30°C above the ambient temperature measured at a distance of one metre away, whilst the installation is operating at its maximum service temperature.'

'The temperature differential between the surface of the cladding and the ambient air must not exceed 20°C at a wind speed of 0 m/s. The ambient temperature is measured one metre away from the insulated face of the installation.'

'The temperature on the cladding must not exceed 60°C.'

2.8 These examples show the serious problems facing the insulation contractor who is required to provide a specification, firm price and some warranties in order to win this work. **In reality such requirements cannot be warranted and do not bear any relationship to the thermal efficiency of the insulation system.** Health and safety requirements of personnel protection are the usual reasons cited for requiring the calculation of surface temperature, to prevent burning of the skin. In addition, in cold applications prevention of surface condensation is clearly advisable.

2.9 For the economics of the parameters to use when calculating heat loss, reference should be made to *FESI Document 6: High profitability with environment protecting insulation layer thicknesses.* For the calculation methods of heat loss/gain, reference can be made to EN ISO 12241: Thermal insulation for building equipment and industrial installations – calculation rules or VDI 2055 Part 1: Thermal insulation of heated and refrigerated operational installations in the industry and the technical building equipment.

2.10 For the unwary there can be the misconception that, in some way, specifying a maximum surface temperature may result in a low heat-flow rate. This perception is wrong. For example, a decrease in the thermal radiation coefficient of the cladding **increases** its surface temperature. However, it **decreases** the heat-flow rate in the system.

2.11 Conversely, an increase in the wind speed decreases the surface temperature of the cladding, but increases heat loss. **Therefore the perception that surface temperature might be an easy measure of the quality of an insulation system is wrong.**

2.12 The objectives of the examples quoted in paragraph 2.7 are more readily achieved through other precautions. If prevention of contact burns cannot be achieved with insulation as dictated by technical or economic considerations, then safety screens or guard rails can be applied. These will ensure contact safety. This subject is further discussed later.

2.13 The prevention of condensation on cold installations can only be reasonably achieved by designing the insulation thickness to ensure that the surface temperature is never below the dew-point temperature. However economically sound, this arrangement is only

practicable if the relative humidity of the ambient air is below 85%, which results in an acceptable surface temperature of the insulation of about 2.5 K below the temperature of the ambient air. For more information reference can be made to *FESI Document 8: Principles of cold insulation.*

3. Detailed consideration of the parameters affecting surface temperature

3.1 Warranties must have a reliable technical or scientific basis and can only be given if the surface conditions are known exactly. Therefore, this paper will evaluate how the different parameters influence the surface temperature.

3.2 Spacer-ring constructions

3.2.1 Whilst with cold insulation, spacer-ring and other supports are usually made of insulation materials or other materials with low thermal conductivity, hot insulation systems usually employ metallic support-rings. These constitute thermal bridges and lead to local surface temperature peaks.

3.2.2 An example of the temperature curve on a hot insulation surface with a metallic support structure is shown in Figure 2.
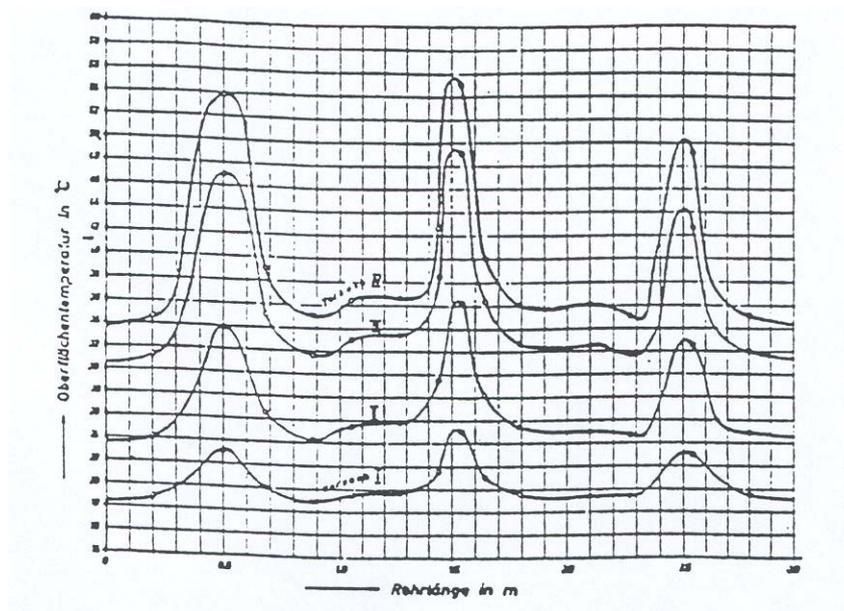
Figure 2:   Graph of temperature distribution on the surface of a metal cladding with spacer-rings and spacers made of 30mm forged steel

3.2.3 In the longitudinal direction steep temperature variation can be seen. In the circumferential direction there is a circular band of increased temperature which is caused by increased heat flow through the spacers.

3.2.4 An additional issue is raised by horizontal pipes and free convection, in buildings for example, as the surface coefficient of heat transfer differs around the circumference (see Figure 3). This results in a temperature variation around the circumference.

3.2.5 Therefore if there is an intention to specify the surface temperature in a contract and then to verify compliance by measurement, then considering the points made in paragraphs 3.2.3 and 3.2.4, the question is - where on the insulated surface should the pre-

determined surface temperature be measured? Clearly this would need to be decided. Three possibilities can be considered.
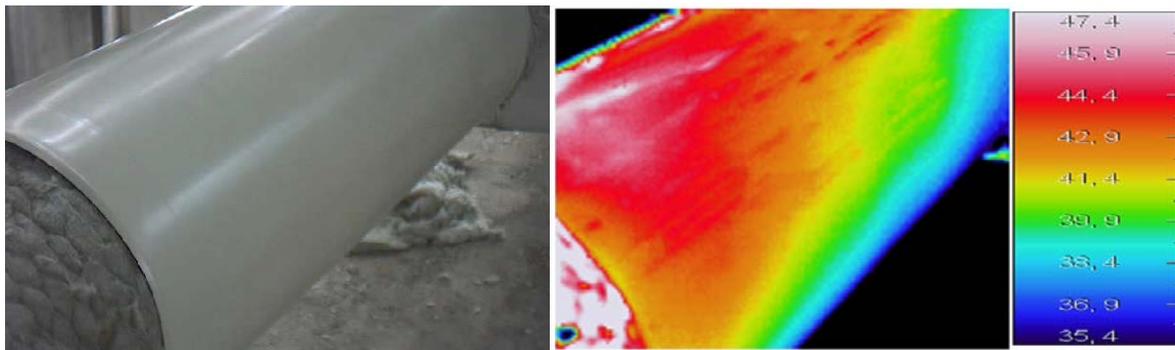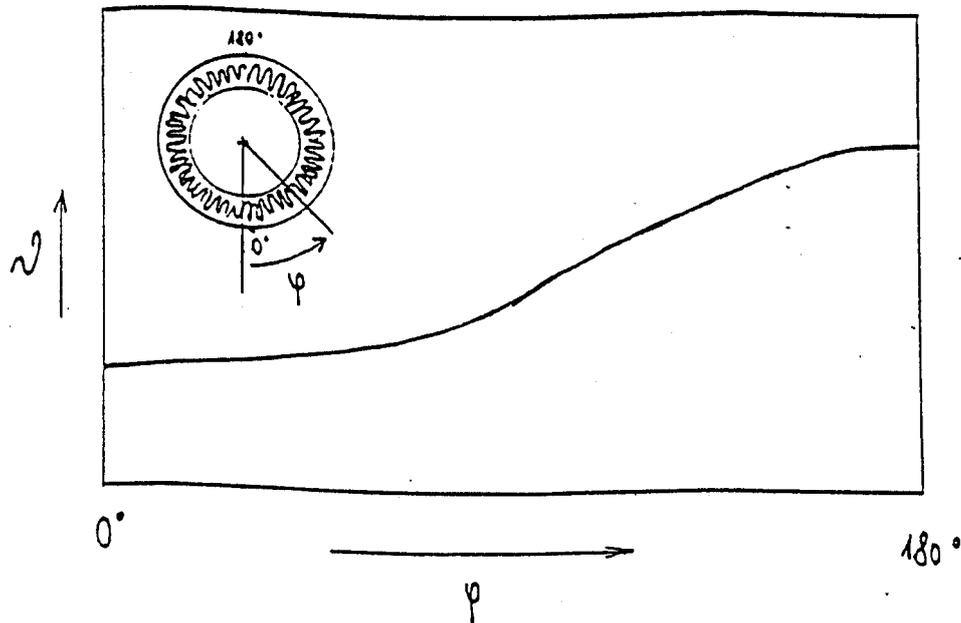
Figure 3: Variation of surface temperatures around the perimeter of a horizontal thermal insulation

3.2.6 Firstly the uninfluenced temperature in the middle between two spacer-rings could be measured. This temperature appears to be easily established, but it does not establish the maximum temperature anywhere on the surface. Additionally, it will be dependent on the point of measurement around the circumference as can be seen in Figure 3.

3.2.7 Secondly perhaps an average temperature could be established over the entire surface. This average temperature appears at first sight to be a reasonable and sound compromise, however, not only it is very difficult to check it as far as measuring technique is concerned, but also it is likely to be a value without any technical significance. The end user or specifier is most likely to be only interested in either the maxima for hot service or the minima for cold service in the steep surface temperature range across the surface.

3.2.8 Finally the maximum surface temperature could be measured over the spacer-ring construction. This value appears to be reasonable as far as contact safety is concerned. However, it results in uneconomical solutions with very high insulation thicknesses as demonstrated in Table 1. The requirement for personnel protection is more readily and economically achieved with other arrangements such as guard rails or safety screens as has been previously mentioned.

3.2.9 On detailed consideration of these three options, none of them are deemed to be technically sensible.

	Surface Temperature in middle between two spacer rings	Longitudal Mean Surface Temperature	Peak Surface Temperature on spacer ring
ϑ_M = 400 °C	ϑ_0 (in °C)	ϑ_m (in °C)	ϑ_S (in °C)
s = 90 mm	54	62	110 – 130
s = 180 mm	35	39	65 – 75

Table 1: An indicative example of surface temperature variation across a pipe insulation

3.2.10 Table 1 is an indicative example of the level of variation of surface temperature across an insulated pipe. The surface temperature ϑ_0 in the middle between two spacer-rings, the longitudinal mean temperature ϑ_m and the peak temperature ϑ_S on a spacer-ring are given for a pipe with nominal diameter of 200mm and a service temperature of 400°C. The ambient temperature is 20°C.

3.2.11 With an insulation thickness of 90mm, a specified maximum surface temperature for personnel protection of 60°C for contact safety is more than achieved in the undisturbed area between two spacer-rings, whilst in the spacer-ring area excessive temperatures in the order of 110°C to 130°C exist. Even doubling the insulation thickness to 180mm would not prevent surface temperatures in the order of 65°C to 75°C occurring on the top of the spacer-ring. This shows that an attempt to achieve contact safety with insulation measures alone must lead to uneconomical solutions.

3.2.12 It must be added that the temperatures ϑ_S given in Table 1 for the surface over the spacer-ring are estimates. The actual temperatures are strongly dependent upon the degree of the contact between object and spacer-ring and between spacer-ring and cladding. Reliable calculation methods to establish the surface temperatures on spacer-rings do not exist.

3.3 Heat transfer conditions at the insulation surface

3.3.1 The surface temperature of an insulation is determined to a significant extent by the surface coefficient of heat transfer which is composed of convection and thermal radiation, whilst the heat loss has very little to do with the surface coefficient.
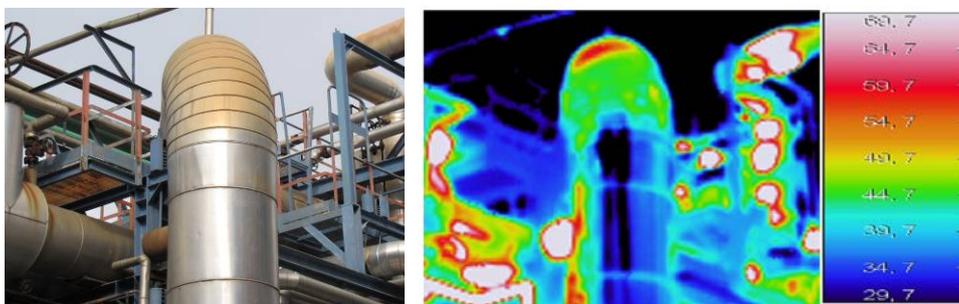
Figure 4: Variation of surface temperature due to a difference in surface emissivity coefficient (oxidized cladding on the elbow – new aluminium cladding on the pipe)

3.3.2 An increase in the surface coefficient of thermal radiation with a wind speed of zero only marginally influences the heat-flow rate, but the surface temperature significantly.

3.3.3 Equally, changing the wind speed will only change the heat-flow rate minimally, however the surface temperature will be changed significantly.

3.3.4 Clearly the surface temperature of an insulation system is no measure of its thermal efficiency.

3.4 Locally different conditions for surface heat transfer

3.4.1 Both the heat transfer through convection and the heat transfer through radiation can differ locally from the heat transfer conditions assumed for the design calculations.

3.4.2 To be on the safe side when considering the surface temperature, the lowest possible coefficient of heat transfer must be selected, whilst for the calculation of heat loss the highest possible coefficient of heat transfer – e. g. through wind speed – must be used. Therefore, to calculate the surface temperature, static ambient air with free convection should always used, since the surface temperature is higher, the lower the surface coefficient of heat transfer.

3.4.3 Free convection is the result of air movement, caused by the ambient air becoming lighter as it is warmed up and therefore rising. Equally, in the vicinity of cold piping, the ambient air becomes heavier and descends. In confined spaces, however, this air movement cannot develop to the extent which is assumed in the formula for the surface heat transfer.
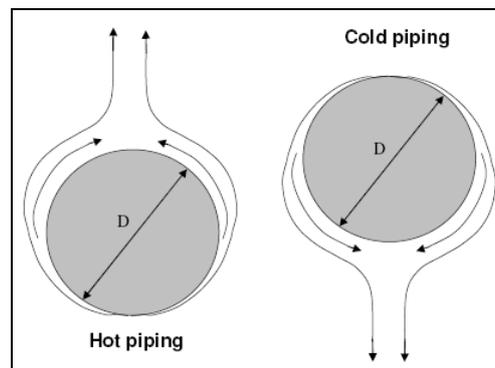
Figure 5: Free convection in hot and cold piping

3.4.4 The surface coefficient of heat transfer through convection, therefore, becomes lower and the surface temperature increases or alternatively decreases in case of cold insulations. The exact local conditions are frequently unknown in the planning phase of an insulation system and, therefore, cannot be taken into account. Additionally, the degree to which convection is hampered, cannot be predicted in advance.

3.4.5 With horizontal pipes, the air movement as a result of differing air densities, which develops under the conditions of free convection, causes differing surface coefficients of heat transfer around the perimeter of the insulation surface. This coefficient is highest at the lowest point of the perimeter and lowest at the apex if the pipe releases heat and causes the ambient air to rise. This causes different surface temperatures. As shown in Figure 3 qualitatively, the surface temperature is lowest on the underside of the pipe and rises continuously around the pipe to the apex.

3.5 Ambient air temperature

3.5.1 In calculating the surface temperature, both the convective and the radiation parts of heat transfer must be taken into account.

3.5.2 Whilst the heat transfer caused by convection is governed by the temperature of the ambient air, the heat transfer through radiation is dependent upon the temperatures of neighbouring surfaces with which the surface in question is in radiation exchange.

3.5.3 As a general rule, the simplifying assumption is made that these neighbouring surfaces have the temperature of the ambient air. However, if other pipe insulations in the close vicinity have the same surface temperature as the insulation in question, then a portion of the heat loss through radiation from the surface is compensated through the radiated heat from the other surfaces. This results in considerably increased temperatures of those areas of the insulation which lie directly opposite the neighbouring surfaces.

3.5.4 If the insulation surfaces face other surfaces of even higher temperatures, the surface temperature is further increased. An extreme example is the radiation from the sun.

3.5.5 Inversely, the heat loss through radiation to the cold clear night sky can cause the surface temperature of the insulation system to fall temporarily below the temperature of the ambient air and may even cause condensation to develop on the surface. This phenomenon is known to occur in external pipework, particularly in exposed areas, and can cause damage through condensation corrosion if the cladding is not vented.

3.5.6 In buildings, there is normally no uniform ambient air temperature. Near vertical pipes and walls, the rising air is warmed so that with increasing elevation the temperature of the ambient air increases. This leads to a continuously rising surface temperature with increasing elevation.

3.5.7 Additionally, especially if pipes run in close proximity to each other, the local air temperature can be considerably above the specified general ambient temperature in the building as a result of heat transfer. It is frequently attempted to circumvent this difficulty by referring to a temperature differential between ambient and surface instead of the surface temperature requiring that the air temperature is measured one metre away from the surface.

3.5.8 The question of whether there was a scientifically arguable distance at which to measure the air temperature has been discussed. There is general agreement that such a distance does not exist and that a selected distance of one metre is arbitrary.

3.5.9 Therefore, in congested areas of plant, the combination of surface temperature-increasing effects, such as increased temperature of the ambient air through heat transfer from other pipes, hampered development of free convection, and reduced heat loss through radiation mean the warranty of a surface temperature is exceedingly difficult under such conditions.

4.   Measurement of surface temperature

4.1 Infra-red thermography is used extensively nowadays so it is important to understand the limitations of this technique. As stated before, extreme caution is counselled when using and interpreting surface temperature using this technique as are highlighted below.

4.2 The evaluation and interpretation of thermographical pictures should only be carried out by trained, certified and experienced personnel.

4.3 Interpreting the resultant images takes much more time than to record them.

4.4 With the majority of installations thermography is **not** possible as surface and/or ambient conditions do not allow for it.

4.5 For pipes running close together, such as along pipe racks or bridges, the thermographical pictures can only be evaluated in connection with extensive surface temperature measurements.

4.6 Solar radiation influences the image information so much that the images become meaningless and cannot be evaluated. Measurements must be taken under dense clouds or at night to have meaning.

4.7 If elimination of outside radiation sources cannot be achieved, then the thermographical images are of limited and qualitative value only.

4.8 Further information on the issues of infra-red thermography can be found in *BFA WK SB Technical Letter No 9 – Methods of measuring and No 10 – Measuring points for thermal measurement.*

5.   Personnel Protection

5.1 If the reason for considering a maximum surface temperature, for above ambient service temperature applications, are for health and safety considerations, then another approach may be required. As has already been discussed in detail, the whole insulated surface of pipework, plant or equipment cannot be guarantied to be below a certain temperature. So in areas such as access platforms where the insulated surfaces that can be accessed by operators then an additional personnel protection guard may be required.
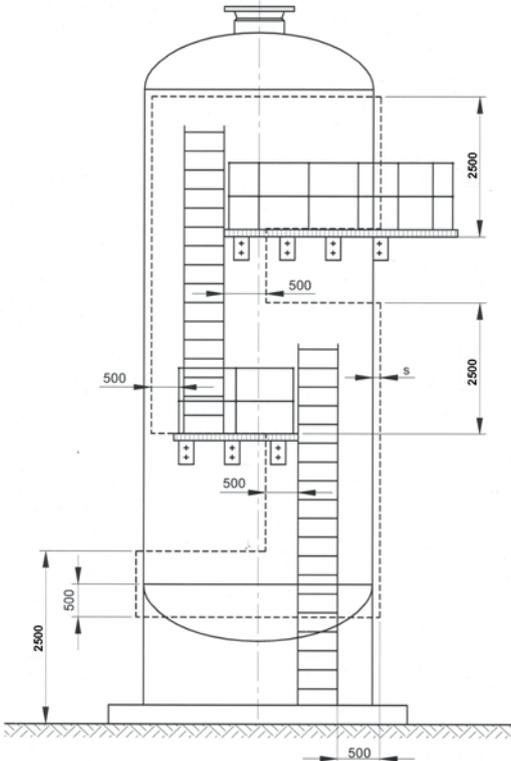
Figure 6:   Example of positioning and dimensions of personnel protection guards

5.2 This can be achieved by fitting a perforated sheet spaced away from the insulated surface in the areas that can be routinely accessed. An example of this principle is shown in Figure 6 where the guarded area is up to 2.5 metres height above the working surface and extends for 0.5 metres horizantally beyond the access area.

5.3 Maximum specified surface temperatures tend to range from 50°C to 60°C.

5.4 This should be based on a temperature that metal cladding reaches in certain areas in the world when exposed to direct sunlight in combination with a certain touch time before skin burning starts.

5.5 The boundaries of these hot areas are defined by CINI as: "*if parts of piping or equipment are less then 2100mm above a work area and within a 800mm reach of such a workplace, platform or stair*". This is detailed in CINI 1.3.19.

6.   Summary

6.1 In practice, the assumed relation between the surface temperature and the thermal insulating value of an insulation system does not exist. The surface temperature does not give an indication of the heat loss. The requirement to warrant the surface temperature of an insulation system has no technical justification, since the surface temperature is dependent upon a number of physical parameters which cannot be calculated or estimated with the necessary degree of certainty. Therefore it cannot be recommended to yield to such a demand. Where the contractor has no choice but to comply, then it is suggested that a large amount of qualification be made, listing the range of assumptions made to simplify the reality back to theory. Clearly with these assumptions in place, then actual temperature measurement is rendered meaningless.

6.2 The requirement for a maximum heat-flow rate stems from intents such as, to save energy, to maintain the conditions for a chemical process or to slow the cooling of a medium. This is the **main aim** of heat retention, the minimisation of heat-flow rates. This cannot be achieved by anything other than insulation.

6.3 The need for a maximum admissible surface temperature of an insulation system can only be justified through concern for personnel protection. External surfaces in contact areas must only be as warm as to prevent risk of burns. However this can more easily be achieved through guard rails or safety screens.

6.4 For cold insulations, maintaining a pre-calculated surface temperature to prevent condensation can be a technically sound requirement and a yardstick for the calculation of the insulation thickness. However, for the reliable prevention of condensation, the influencing parameters discussed here, such as reduced coefficients of heat transfer, low temperatures of the ambient air where pipes run in close proximity, reduced thermal radiation through adjacent surfaces of the same temperature, must also be taken into consideration.

6.5 A reliable and economically sensible prevention of dew formation can only be achieved up to a relative humidity in the ambient air of less than 85%.

7. Conclusion

7.1 In conclusion, for all of the reasons above, when applying thermal insulation it cannot be recommended to warrant the surface temperatures.

8. Further information

More detailed information or advice can be obtained from the insulation contracting industry association in your country via the FESI website www.fesi.eu .

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