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Investigation of Condensation Problem on Chilled Water Piping

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Chilled water pipes are insulated for energy efficiency, avoiding heat gain to the chilled water and preventing surface condensation. In most cases, the insulation is installed following standard specifications as it is not expected to be an area of concern for typical air conditioning systems. However, this may not be the case when considering humid climates. Unless selected carefully and installed with attention to good workmanship, the chilled water pipe insulation could lead to problems in humid climates. This article reviews a case where problems with the chilled water pipe insulation became the centre of investigation due to surface condensation.

Background

The project where the condensation problem occurred is at an industrial facility in Singapore. The central chilled water plant, comprising 4 nos. 2,500 TR chillers, provides chilled water to serve process and comfort air conditioned areas. The central plant is installed in the Utility Building, which is separate from the manufacturing block requiring the chilled water. The chilled water piping passed through external areas, exposed to outside conditions and internal areas.

The pipework insulation material used for this project was a cellular type glass insulation. The specifications called for the insulation material to be applied to bare pipes with a coat of mastic, and then, strapped using stainless steel bands and finally, covered with stainless steel jacketing. The key properties of the insulation material used were as follows:

- Suitable for operating temperatures from –268 °C to +482 °C
- Thermal conductivity: 0.04 $W/(m^2 \cdot K)$ @ 10°C
- Water vapour permeability: 0.00 perm-cm (insulation material itself is an inherent vapour barrier)
- Moisture absorption (% by volume): 0.2

Condensation on the outer surface of insulation jacketing occurred when the plant was commissioned and the chilled water system brought into operation. The condensation, however, was not present over the whole system, occurring only on certain sections of straight pipework, at fittings and at the pipework supports.. The condensation in some cases was not consistent and appeared only at certain specific times of the day.

The surface condensation was classified as a problem and the authors of this article were invited to investigate the problem.

Methodology

The investigation of the condensation problem was carried out by adopting the approach as shown in **Figure 1**. This involved running parallel activities in the following three key areas:

GENERIC TYPES OF INSULATION

1. Fibrous Insulation: Composed of small diameter fibers which finely divide the air space. The fibers may be perpendicular

or horizontal to the surface being insulated, and they may or may not be bonded together. Silica, rock wool, slag wool and alumina silica fibers are used. The most widely used insulation of this type are glass fiber and mineral wool.
2. Cellular Insulation: Composed of small individual cells separated from each other. The cellular material may be glass or foamed plastic such as polystyrene (closed cell), polyurethane, polyisocyanurate, plyolefin, and elastomeric.
3. Granular Insulation: Composed of small nodules which contain voids or hollow spaces. It is not considered a true cellular material since gas can be transferred between the individual spaces. This type may be produced as a loose or pourable material, or combined with a binder and fibers to make a rigid insulation. Examples of these insulations are calcium silicate, expanded vermiculite, perlite, cellulose, diatomaceous earth and expanded polystyrene.

I. Field observations

The field observations were focused on the following three issues:

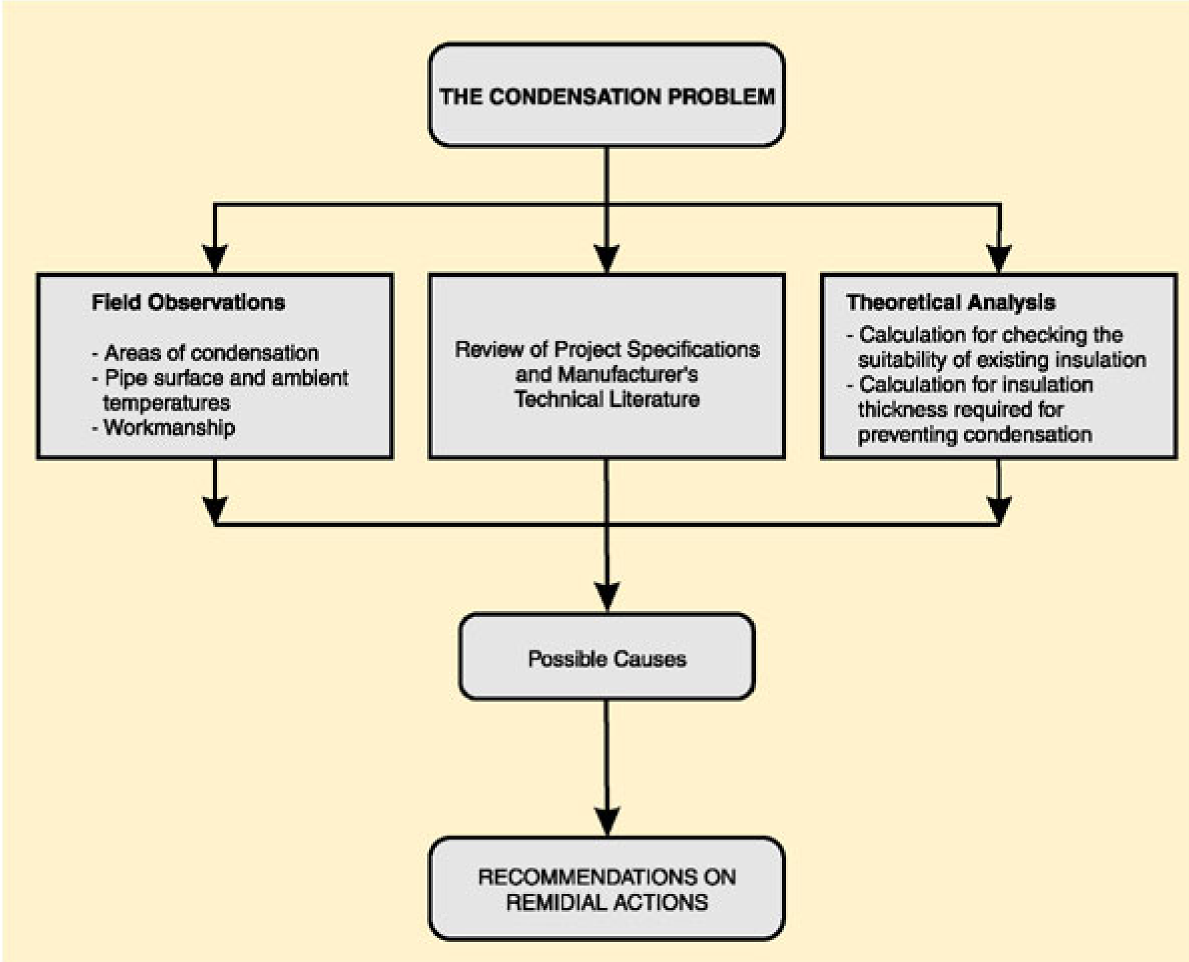
- Identifying the areas where condensation occurred
- Measurement of chilled water pipe surface temperature and prevailing ambient conditions (dry bulb, wet bulb, and dew point temperature)
- Workmanship of the installation

II. Review of project specifications and manufacturer's technical literature

III. Theoretical analysis

Theoretical analysis, involving calculations for pipe surface temperature based on various parameters, such as the K value of insulation material, ambient conditions, etc., was carried out to check the following:

- Whether the existing insulation was suitable for preventing condensation on the surface of chilled water piping
- What needed to done if the condensation were to be avoided



Figuer 1 Methodology of investigation

Findings

The findings of the investigation fall into three key categories: field observations, project specifications and theoretical analysis.

Field Observations – Temperature Measurements and Areas of Condensation

Measurements of the chilled water insulation surface temperature and prevailing ambient conditions (dry, wet bulb and dew point temperatures) were carried out at six different locations. Two locations were external and four internal. The temperature measurements were carried out over a period of four days and were varied to allow measurement during different hours of the day to produce readings around the clock (including late night and early morning hours). The measurements were carried out at specific points where problems had been identified i.e. straight lengths of pipe, pipework supports, flanged joint, elbow and valves, etc.

Table 1 shows the summary of the measurements for the prevailing ambient conditions.

Table 1 Summary of prevailing ambient conditions based on site measurements

	Dry Bulb Temp. (°C)	Relative Humidity	Remarks
External areas	29.1-30.0	76-80%	9 out of 25 occurrences (max. simultaneous)
	range not relevant*	76-80%	12 out of total 25 occurrences
	range not relevant*	81-85%	2 out of total 25 occurrences
	range not relevant*	86-90%	nil
Internal areas	28.1-29	76-80%	8 out of total 31 occurrences (max.
	range not relevant*	76-80%	simultaneous)
	range not relevant*	81-85%	16 out of 31 occurrences
	range not relevant*	86-90%	6 out of total 31 occurrences
			2 out of total 31 occurrences

* It was identified that ambient dry bulb temperature was not relevant for resolving the condensation problem and the effect was driven by the relative humidity. This is discussed later.

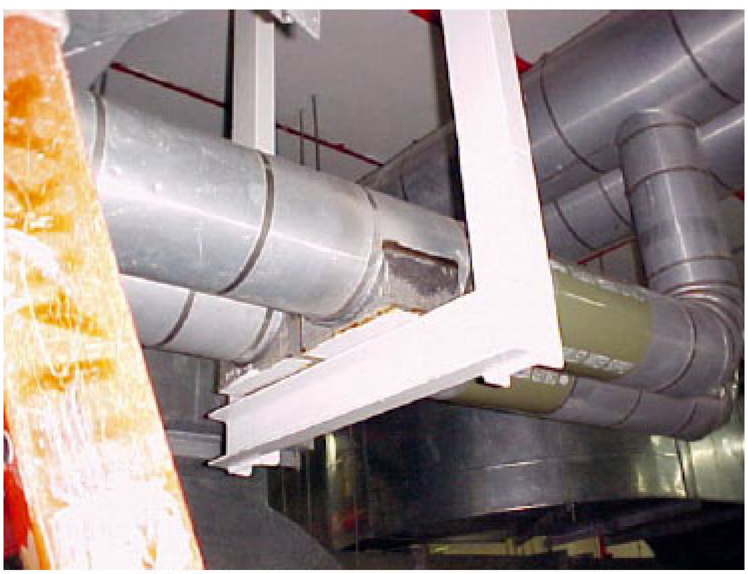


Photo 1 : Condensation on pipe support

It is important to note from Table 1 that the relative humidity was in the range of 76-80% most of the time, but it could peak at 90% on certain occasions.

The pipe surface temperature measurements revealed the following:

- On the straight runs of pipe, the surface temperature was approximately 2°C above the prevailing dew point temperature; during the course of investigation no condensation was observed on the straight runs of chilled water pipe. This observation, however, did not confirm that there was no problem, as would be evident from the discussion on theoretical analysis later in the article.

- The surface temperature measured at pipe fittings – elbows, flanges, valves, etc. – was on average below the prevailing dew point temperature; many fittings showed clear evidence of surface condensation.

Photo 2 : Gap between adjacent pieces of insulation

Having carried out the insulation surface temperature measurements, it was found that although the same insulation material and thickness was used throughout, the insulation on the pipe fittings was providing lower thermal performance as compared to the straight runs of the pipe. The reason for this was identified as a workmanship defect and is explained in the next section.

Field Observations – Workmanship

Chilled water pipe insulation was removed from select locations to review the workmanship of the installation. The inspection revealed that there were deviations from the manufacturer's installation guidelines. The key ones are mentioned below:

- Inadequate spread of mastic for bonding the insulation onto the surface of the pipe and also for joining the adjacent pieces of insulation.
- Large gaps between adjacent pieces of insulation.
- Hollow spaces without any insulation around complex fittings, such as flanges, valves, etc.
- Adjacent pieces of insulation not staggered and overlapped as per the specifications and manufacturer’s recommendations.

- Valve/instrument stems in direct contact with insulation jacketing, forming cold bridge. This was one of the main causes for condensation around the valves.
- No valve stem spacers on motored valves to allow over insulation, leaving exposed surfaces.
- Cold bridging at the pipework supports due to uclamp bolting direct to pipe with no thermal break. Also, the thickness of insulation at edge of the clamp was insufficient.

Most of the workmanship issues were manifested at the pipe fittings, such as valves, elbows, flanges, etc., where specifications called for an elaborate arrangement.

Review of Project Specifications

The review of project specifications and the manufacturer's technical literature revealed the following three key issues regarding design ambient conditions, insulation thickness and insulation jacketing:

- Design Ambient Conditions

Insulation specifications, in particular, did not indicate the design ambient conditions. However, the design was based on the following outdoor conditions mentioned elsewhere in the general air conditioning specifications and the same were also assumed to apply to the insulation material:

Dry Bulb Temperature: 33.3°C
Wet Bulb Temperature: 27.8°C

The manufacturer's technical literature, however, qualified the design ambient conditions as follows:

"Designers are cautioned that calculating average ambient conditions for a particular location may provide quite reasonable insulation thickness values, but this is likely to result in a significant number of days during which sweating and dripping of condensate occur."

Photo 3 : Exposed valve stem without insulation

The above statement is significant as it is not uncommon to state design outdoor conditions in the general section of air-conditioning specifications and omitting the same information in the section on insulation specifications.

Table 2 : Thickness of insulation as per project specifications and manufacturer's recommendations

	Pipe size/Insulation thickness (mm)					
	100 NB	**150 NB**	**200 NB**	**250 NB**	**300 NB**	**400 NB**
Project specifications	45	45	50	50	50	50
Manufacturer's recommendation (90% relative humidity)	63.5	63.5	63.5	63.5	76.2	76.2

• Insulation Thickness

Manufacturer's technical literature provided recommendations on the thickness of insulation for different ambient humidity levels. The thickness of insulation specified in the project exceeded the values recommended in manufacturer's literature at ambient relative humidity level up to 80% but fell short of recommendation for 90% humidity. **Table 2** shows the difference between thicknesses specified for the project and the manufacturer's recommendations.

It is evident that the designers did not follow manufacturer's recommendations and compromised the thickness of insulation for 90% and above humidity levels.

• Metal Jacketing

Project specifications required stainless steel jacketing to be applied over the insulation. The manufacturer's literature, however, cautioned against the use of highly reflective materials as follows:

"On piping and equipment with operating temperatures below ambient, highly reflective materials with low emissivity, such as unpainted metal jacketing, will decrease heat gains. As a result, the surface temperature will be reduced and the potential for condensation will increase. When designing below-ambient insulation systems for maximum condensation protection, less reflective materials with higher emissivity such as painted metal, PVC, PIB sheet, ASJ or mastic should be selected for the outer surface of the insulation system."

This is again an area often overlooked while specifying the type of jacketing over chilled water piping insulation.

Theoretical Analysis

In addition to the field observations and review of project specifications, a theoretical analysis was carried out to check the following:

- Suitability of insulation under the most challenging conditions.
- The required thickness of insulation if the condensation were to be avoided.

The analysis involved using the following formulae for steady state heat transfer for a hollow cylindrical geometry:

(1) $q = U A \Delta T$

where, q: Rate of heat transfer (W)

U: Overall heat transfer coefficient W/(m²•K)

A: Area based on inner radius of pipe (m2)

ΔT: Temperature difference in K (ambient dry bulb temperature – chilled water temperature)

(2) $$\frac{1}{U} = \frac{1}{h_i} + \frac{r_1 \, Ln(r_2 / r_1)}{K_{pipe}} + \frac{r_1 \, Ln(r_3 / r_2)}{K_{insulation}} + \frac{r_1}{h_o r_3}$$

where,

h_i : Convection heat transfer coefficient at inner surface of chilled water pipe [W/(m²•K)]

h_o : Convection heat transfer coefficient at outer surface of insulated chilled water pipe [W/(m²•K)]

r_1 = Inner pipe radius (m)

r_2 = Outer pipe radius (m)

r_3 = Outer radius of insulated pipe (m)

K_{pipe} = Thermal conductivity of pipe material [W/(m²•K)]

$K_{insulation}$ = Thermal conductivity of insulation material [W/(m²•K)]

(3) $q = (T_2 - T_1) / R_1 = (T_3 - T_2) / R_2$

where,

T_1 : Temperature at the inside surface of chilled water pipe

T_2 : Temperature at the junction of outer surface of chilled water pipe and inner surface of pipe insulation

T_3 : Temperature at the outer surface of chilled water pipe insulation

R_1 : Thermal resistance of pipe material

R_2 : Thermal resistance of insulation material

$$R_1 = \frac{r_1 \operatorname{Ln}(r_2 / r_1)}{K_{pipe}}$$

$$R_2 = \frac{r_1 \operatorname{Ln}(r_3 / r_2)}{K_{insulation}} \quad (4)$$

The above formulae were set-up on an Excel spreadsheet to calculate the chilled water pipe surface temperature for different conditions. All the calculations were performed for a sample case of 350 mm diameter pipe (as found on site).

Results of Theoretical Analysis

In order to carry out the theoretical analysis, the starting point was to establish the most challenging ambient conditions. Using the meteorological data recorded for Singapore for the period Jan 1981 to Dec 1999, it was concluded that the conditions with humidity levels ranging from 86% to 90% were the most challenging. Although, there were occurrences of humidity levels above 90%, such conditions were deemed to be close to precipitation, and therefore not considered. Moreover, when conditions with humidity levels above 90% occurred, there remains a very little gap (~ 1-1.5 °C) between the ambient dry bulb and dew point temperatures. Selections based on tolerances as tight as this would always be subject to condensation as small fluctuations in operating parameters and ambient conditions (wind, emissivity, etc.) could easily lead to pipe surface temperature dropping below the ambient dew point temperature. For the purpose of analysis, 90% relative humidity was considered as the limiting condition. If condensation occurred at 90% relative humidity, then one could conclude that it would also occur at humidity levels above 90%.

The key figures set-up on the Excel spreadsheet for the theoretical calculations are as shown in **Table 3**.

Table 3 Ambient conditions for theoretical analysis

Ambient dry bulb temperature °C	28	27	26	25	24
Ambient wet bulb temperature °C	26.6	25.7	24.7	23.7	22.8
Ambient relative humidity %	90	90	90	90	90
Ambient dew point °C	26.2	25.2	24.2	23.3	22.3

The calculations for chilled water pipe surface temperature were carried out for the limiting condition of 90% relative humidity at ambient dry bulb temperatures ranging from 24 °C to 28 °C.

The other input parameters are as below:

- Chilled water temperature: 6 °C
- Pipe NB: 350 mm
- Pipe OD: 355.6 mm
- Pipe material: Carbon steel (K=50 W/(m^2•K)
- Insulation thickness: 50 mm
- Insulation K value: 0.04 W/m^2•K
- Airside convection coefficient: 7.5 W/m^2•K (still air, emissivity=0.4)
- Waterside convection coefficient: 3600 W/m^2•K

The results of the calculation are summarised in **Table 4**.

Table 4 : Summary of results from theoretical analysis

Ambient dry bulb temperature °C	28	27	26	25	24
Ambient relative humidity %	90	90	90	90	90
Ambient dew point °C	26.2	25.2	24.2	23.3	22.3
Pipe surface	26.1	25.2	24.3	23.4	22.4

temperature °C					
Condensing (Yes/No)	Yes	Yes	No	No	No

As revealed by the results in **Table 4**, the existing insulation was not sufficient for preventing condensation at 90% relative humidity levels.

In order to find out the required thickness of insulation to prevent condensation, the calculations were repeated with insulation thickness increased from 50 mm to 75 mm and the results of that calculation are shown in **Table 5**.

Table 5 : Summary of results for increased thickness of insulation

Ambient dry bulb temperature °C	28	27	26	25	24
Ambient relative humidity %	90	90	90	90	90
Ambient dew point °C	26.2	25.2	24.2	23.3	22.3
Pipe surface temperature °C	26.8	25.8	24.9	23.9	23
Condensing (Yes/No)	No	No	No	No	No
Required insulation thickness (mm)	75	75	75	75	75

As reflected by the results in **Table 5**, condensation could be narrowly avoided if the thickness of insulation was increased to 75 mm. Since, the increased thickness of insulation would help to prevent condensation under the most challenging conditions (90% relative humidity), it would be sufficient for avoiding condensation under the less challenging conditions (with relative humidity levels below 90%).

Conclusion

The findings of the investigation can be summarised as on the following page:

1. The insulation material was specified without due consideration to the most challenging ambient conditions (90% humidity in the present case) applicable to external or mechanically ventilated areas.
2. Manufacturer's recommendations were not followed, firstly for the recommended thickness of insulation and secondly, for incorporating reflective jacketing over the insulation without compensating for the loss of radiant heat.

3. The installation was not carried out as per the specifications and the general workmanship was poor. As a result, most of the pipe fittings were experiencing heavy condensation.
4. Important issues for consideration.
   a. Standard insulation specifications should be reviewed to ensure that specific clauses are included for installations in tropical climates i.e. qualifying the assumptions for base specification.
   b. Designers should ensure that installation quality checks are carried out on site to avoid problems associated with poor workmanship. This is often missed as the insulation jacketing hides the evidence.
   c. Particular attention should be paid to detailing the pipework supports and insulation of awkward fittings. If this is over complicated, the chances of failure due to workmanship are high.
   d. Insulation K value is the biggest influencing factor for thermal performance. Standard specifications should be updated periodically to reflect the advances in insulation material technology.

Chilled water pipe insulation may appear to be a standard and routine part of all air conditioning projects but overlooking it in the design and installation processes could lead to substantial problems, especially in humid climates.