



Principles of Cold Insulation

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1. Introduction

The main duty of all insulation systems is the minimisation of heat-flow rates.

With hot insulation, the heat-flow rate is from the object towards the ambient air, with cold insulations, from the ambient air to the object. The FESI Technical Lexicon defines “Cold insulation” as follows:

“Assembly of components which reduces heat gain to the cold medium. Components may include insulating materials, supports, load-bearing construction, vapour barrier and outer covering.”

The “principles of cold insulation” set forth in this paper apply whenever the medium temperature is below the temperature of the ambient air.

With cold insulations, there is always the danger of moisture entering the insulation material. The moisture is caused through condensation of water vapour out of the ambient air, whenever the temperature is below the dew point at the object or inside the insulation material, providing there is water vapour at this point.

The mass of the condensing water vapour is limited to the mass of the intruding water vapour. Water vapour will be transported by differences in the overall pressure (air movement) and through differences in the partial water vapour pressure (water vapour diffusion) between the ambient air and the insulation.

Minimisation of moisture in the insulation is the prime consideration in the design of a cold insulation. If this danger is not prevented, water and/or ice form at those parts of the insulation system where the temperature is below the dew-point temperature.

For the following reasons it is important that water and ice must be kept out of any insulation system:

- In the insulation material they reduce the insulating effect considerably. The thermal conductivity of water is 20 times that of air [$\lambda_{\text{air}} \approx 0,03 \text{ W}/(\text{m} \cdot \text{K})$]; [$\lambda_{\text{water}} \approx 0,6 \text{ W}/(\text{m} \cdot \text{K})$]; the thermal conductivity of ice is 100 times that of air [$\lambda_{\text{ice}} \approx 3 \text{ W}/(\text{m} \cdot \text{K})$].
- Water can cause corrosion on insulated installations and on the inner surface of the cladding, unless protective measures have been taken.
- Water and ice increase the weight of the insulation. Cold piping can collapse under this additional load.

2. Physical principles causing water vapour transmission and the formation of dew

2.1 Relative humidity

Air contains water vapour. The amount of water vapour, which the air can ultimately absorb, is dependent upon the temperature and increases with it (see next table).

The maximum water vapour percentage, air can accommodate at a given temperature, is called 100% relative humidity. The amount of water vapour actually present in the air is expressed in relation to this possible maximum at the defined temperature: “80% relative humidity at an air temperature of 20 °C” means that the moisture actually present in the 20 °C warm air at the moment of measurement was 80% of what air at 20 °C would ultimately be able to absorb.

2.2 Dew

Dew (formerly called “condensation water”) is water condensing out of the air whenever the temperature is below the dew point. The dew-point temperature is dependent upon the condition of the air (temperature and relative humidity, e. g. 20 °C and 80%). It is undercut when the air containing moisture is cooled down to an extent that – due to a constant amount of water vapour – now has a relative humidity of 100% at the newly obtained – lower – temperature, and as a result water condenses. This can happen in the open air as fog, but also through contact with cold objects as dew at the surface of these objects.

The permissible cooling of surfaces dependent upon the temperature and relative humidity of the air is shown in the table below:

Air temperature °C	Maximum water vapour content g/m ³	Permissible cooling of air in °C until dew formation at a relative air humidity of													
		30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
-30	0,35	11,1	9,8	8,6	7,5	6,6	5,7	4,9	4,2	3,5	2,8	2,2	1,6	1,1	0,6
-25	0,55	11,5	10,1	8,9	7,8	6,8	5,9	5,1	4,3	3,6	2,9	2,3	1,7	1,1	0,6
-20	0,90	12,0	10,4	9,1	8,0	7,0	6,0	5,2	4,5	3,7	2,9	2,3	1,7	1,1	0,6
-15	1,40	12,3	10,8	9,6	8,3	7,3	6,4	5,4	4,6	3,8	3,1	2,5	1,8	1,2	0,6
-10	2,17	12,9	11,3	9,9	8,7	7,6	6,6	5,7	4,8	3,9	3,2	2,5	1,8	1,2	0,6
-5	3,27	13,4	11,7	10,3	9,0	7,9	6,8	5,8	5,0	4,1	3,3	2,6	1,9	1,2	0,6
0	4,8	13,9	12,2	10,7	9,3	8,1	7,1	6,0	5,1	4,2	3,5	2,7	1,9	1,3	0,7
2	5,6	14,3	12,6	11,0	9,7	8,5	7,4	6,4	5,4	4,6	3,8	3,0	2,2	1,5	0,7
4	6,4	14,7	13,0	11,4	10,1	8,9	7,7	6,7	5,8	4,9	4,0	3,1	2,3	1,5	0,7
6	7,3	15,1	13,4	11,8	10,4	9,2	8,1	7,0	6,1	5,1	4,1	3,2	2,3	1,5	0,7
8	8,3	15,6	13,8	12,2	10,8	9,6	8,4	7,3	6,2	5,1	4,2	3,2	2,3	1,5	0,8
10	9,4	16,0	14,2	12,6	11,2	10,0	8,6	7,4	6,3	5,2	4,2	3,3	2,4	1,6	0,8
12	10,7	16,5	14,6	13,0	11,6	10,1	8,8	7,5	6,3	5,3	4,3	3,3	2,4	1,6	0,8
14	12,1	16,9	15,1	13,4	11,7	10,3	8,9	7,6	6,5	5,4	4,3	3,4	2,5	1,6	0,8
16	13,6	17,4	15,5	13,6	11,9	10,4	9,0	7,8	6,6	5,5	4,4	3,5	2,5	1,7	0,8
18	15,4	17,8	15,7	13,8	12,1	10,6	9,2	7,9	6,7	5,6	4,5	3,5	2,6	1,7	0,8
20	17,3	18,1	15,9	14,0	12,3	10,7	9,3	8,0	6,8	5,6	4,6	3,6	2,6	1,7	0,8
22	19,4	18,4	16,1	14,2	12,5	10,9	9,5	8,1	6,9	5,7	4,7	3,6	2,6	1,7	0,8
24	21,8	18,6	16,4	14,4	12,6	11,1	9,6	8,2	7,0	5,8	4,7	3,7	2,7	1,8	0,8
26	24,4	18,9	16,6	14,7	12,8	11,2	9,7	8,4	7,1	5,9	4,8	3,7	2,7	1,8	0,9
28	27,2	19,2	16,9	14,9	13,0	11,4	9,9	8,5	7,2	6,0	4,9	3,8	2,8	1,8	0,9
30	30,3	19,5	17,1	15,1	13,2	11,6	10,1	8,6	7,3	6,1	5,0	3,8	2,8	1,8	0,9
35	39,4	10,2	17,7	15,7	13,7	12,0	10,4	9,0	7,6	6,3	5,1	4,0	2,9	1,9	0,9
40	50,7	20,9	18,4	16,1	14,2	12,4	10,8	9,3	7,9	6,5	5,3	4,1	3,0	2,0	0,9
45	64,5	21,6	19,0	16,7	14,7	12,8	11,2	9,6	8,1	6,8	5,5	4,3	3,1	2,1	0,9
50	82,3	22,3	19,7	17,3	15,2	13,3	11,6	9,9	8,4	7,0	5,7	4,4	3,2	2,1	0,9
55	104,4	23,0	20,2	17,8	15,6	13,7	11,8	10,2	8,6	7,1	5,8	4,5	3,2	2,1	0,9
60	130,2	23,7	20,9	18,4	16,1	14,1	12,2	10,5	8,9	7,3	5,9	4,6	3,3	2,1	0,9
65	161,3	24,5	21,6	19,0	16,6	14,5	12,6	10,8	9,1	7,6	6,1	4,7	3,4	2,1	0,9
70	198,2	25,2	22,2	19,5	17,1	15,0	13,0	11,1	9,4	7,8	6,2	4,8	3,4	2,1	0,9
75	242,0	26,0	22,9	20,1	17,7	15,4	13,3	11,4	9,6	8,0	6,4	4,9	3,5	2,2	0,9
80	293,4	26,8	23,6	20,7	18,2	15,8	13,7	11,7	9,9	8,2	6,6	5,0	3,6	2,2	0,9

The table shows that e. g. at an air temperature of 20 °C and a relative humidity of 60%, a surface must not have a temperature reduction of more than 8 K to avoid dew condensation on it. The surface, therefore, must not get colder than 12 °C.

This permissible temperature difference decreases drastically, as the relative humidity increases. On the same line – at air temperature of 20 °C – the permissible temperature difference to avoid dew formation at a relative humidity of 90% is only 1,7 K, i. e. at this very high relative humidity, a fairly small temperature difference – here 1,7 K – is sufficient to cause dew formation at the surface.

2.3 Moisture transmission through air movement

Air movement is a transportation process caused by differences in the overall pressure. When points of differing air pressure are not isolated from each other in an air-tight manner, air will flow from the area of higher pressure to the area of lower pressure until equilibrium is reached. If the temperature changes in this process, because e. g. a lower temperature prevails at the point of lower pressure, the water vapour contained in the inflowing air will condense as soon as the temperature is below the dew point.

Air movement will transport great amounts of moisture in short periods.

2.4 Moisture transmission through water vapour diffusion

Water vapour diffusion is a process of transporting water vapour because of differences in the concentration or the partial water vapour pressure at an equal overall pressure. If different partial water vapour pressures prevail on either side of a membrane which is not water-vapour-diffusion-tight, water is transported towards the area of lower partial pressure, until the two partial water vapour pressures are at equilibrium.

Relatively small amount of moisture are transported through water vapour diffusion.

3. Duties of cold insulation

The function of cold insulation is:

- ☞ reduction of heat flow rate;
- ☞ minimisation of moisture condensation at the surface of the object, to achieve this:
 - a water vapour retarder **minimises** the water vapour diffusion into the insulation material and
 - the use of closed cell insulation materials **prevents** air movement in the insulation.
- ☞ prevention of dew condensation at the surface of the insulation, to achieve this:
 - sufficient thickness of insulation is calculated.

Since a number of conditions, which the insulation contractor cannot influence, also contribute to the completion of this task, the service and environmental conditions for which the cold insulation is to be designed must be specified precisely. If no firm values can be given, e. g. because air pressure and relative humidity vary over the year, assumptions must be made and be agreed upon.

Conditions to be provided by the client:

- ambient temperature,
- relative humidity of the ambient air,
- service temperature.

Conditions which frequently can only be assumed for the design of the insulation system:

- overall geometry of the installation,
- radiation conditions at the surface of the cladding,
- conditions of air movement and convection at the surface of the cladding,
- conditions of heat transfer at the surface of the cladding.

A sufficient insulation thickness is needed to prevent dew condensation at the surface of the insulation. Next to ambient temperature, temperature of the medium, relative air humidity and thermal conductivity of the insulation material, the surface coefficient of heat transfer between insulation surface and ambient air is of decisive importance for its calculation. To determine the insulation thickness, conditions such as inhibited convection due to close spacing or inhibited radiation conditions must be taken into account.

When deviating from the agreed ambient air conditions, temporary dew condensation cannot be avoided.

4. Moisture in cold insulations

Water vapour can enter the insulation in two ways. In the order of importance, these are air movement and water vapour diffusion.

4.1 Ingress of moisture through air movement

Open cell insulation materials are not suitable for cold insulation as they do not resist air movement and water vapour diffusion. If they are used anyway, air movement is the principal reason for substantial water accumulation in the insulation material and at the object.

with closed cell insulation materials, the risk of air movement is restricted to cavities, gaps and joints.

The insulation system forms a cavity between the object on one side and the cladding on the other, which is exempting the insulation material initially filled with air of atmospheric pressure. As the atmospheric pressure changes, a pressure difference occurs between the ambient air and the insulation "cavity".

Under service conditions, the mean temperature in the insulation is dependent upon both the temperature of the medium and of the ambient air. Changes in these temperatures lead to temperature differences in the insulation and thereby again to differences in pressure following the physical laws for gases. The insulation "breathes" and is continuously invaded by moisture in the form of water vapour through air exchange, if it is not sealed tightly against air movement.

Water vapour retarders fitted in practice cannot be made permanently tight against air movement because of unavoidable joints in the adhesive. The moisture entering the system with the air flux would condense inside the insulation layer. The condensing dew would remain inside the system and at the next turn of the pressure difference, relatively dry air would leave the insulation, since the water would not evaporate fast enough because of its relatively high evaporator enthalpy (heat of evaporation). With repeated occurrences of this process, one speaks of a “pumping effect”.

To **avoid** this pumping effect, closed cell insulation materials are compulsory with cold insulations (see also AGI working document Q 03, table 2). Exceptions are e. g. air-separation installations. In these cases, a double-skin covering must be constructed.

If lining-pieces are used, the joints must be completely closed against air movement by being totally filled with adhesive.

4.2 Ingress of moisture through water vapour diffusion

Opposite to air movement, water vapour diffusion is a moisture transportation caused by differences in the partial water vapour pressure. It is a transportation process of water vapour caused by concentration or partial pressure differences. Due to the temperature and partial pressure conditions in cold insulations, the direction of diffusion is generally towards the insulated object. This leads to moisture accumulating in the insulation; the thermal conductivity increases accordingly.

4.3 Water vapour retarders

Water vapour diffusion is supposed to be **minimised** through the “water-vapour-diffusion-tight” water vapour retarder. Air movement is supposed to be **prevented** by a combination of water vapour retarder and closed cell insulation material.

Nowadays, one speaks of **water vapour retarder**; despite the fact that generally **vapour-tight** materials are being used.

This verbiage reflects the fact that total prevention of air exchange and water vapour diffusion would only be possible by an absolute air-movement- and diffusion-tight outer covering of the insulation material. This can only be achieved through very high technical effort. There are enough practically vapour-tight materials available, e. g. metal foils or sheets, however, there are no cost-effective means of air-movement- and vapour-tight closing at joints and fittings. A compromise is therefore needed and has to be content with the minimisation of moisture ingress into the insulation material.

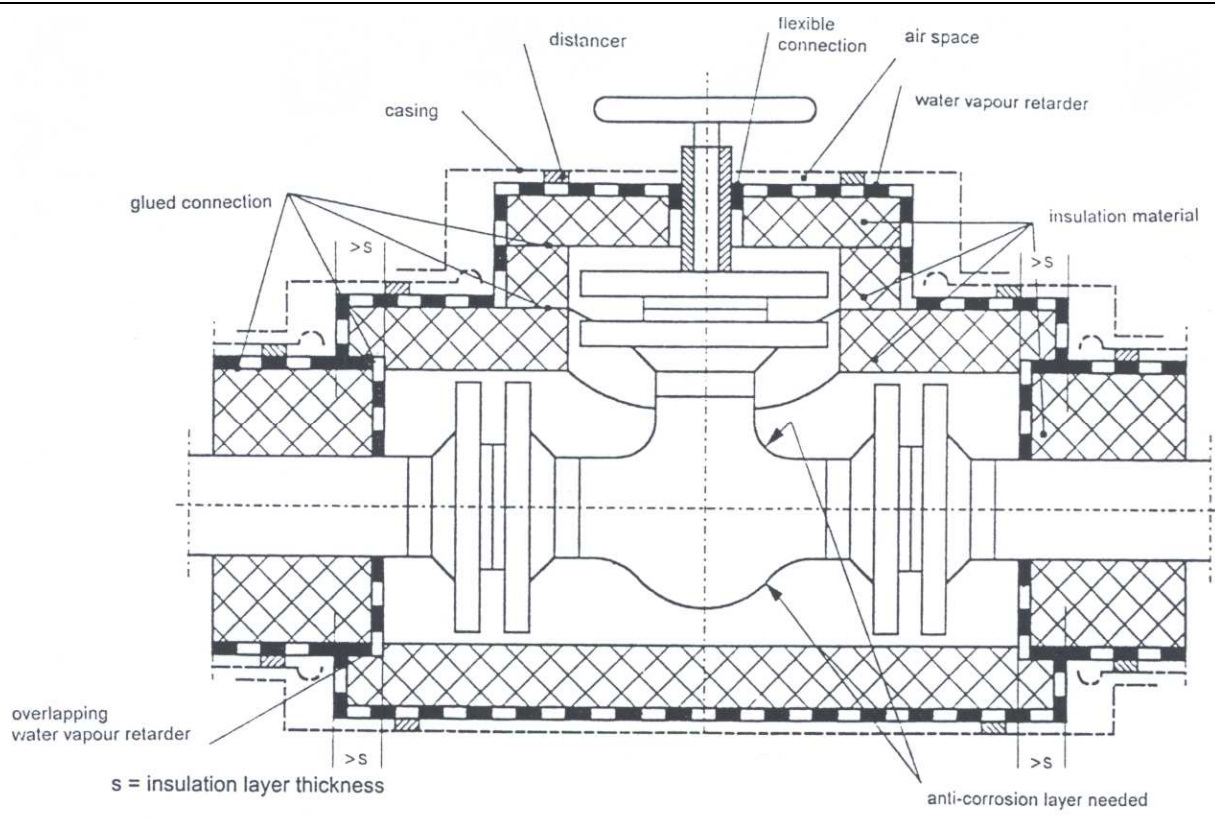
The ingress of moisture to the insulation material must be reduced to the technically feasible minimum. The moisture transport through vapour diffusion is minimised by the use of water vapour retarders of metal foils glued to the insulant, metal-sheet claddings and permanently flexible joints at seams, plastic bandages and so on. The entire surface of the water vapour retarder must be glued to the insulation material, since otherwise air flowing through smallest damage of the water vapour retarder could use the entire non-glued surface of the insulation material for diffusion processes.

4.4 Evaluation

If moisture ingress through air flow occurs, its effect exceeds the effect of water vapour diffusion exponentially. Therefore, the use of closed cell insulation materials in connection with an air-draught-tight execution of a water vapour retarder is more important than the water vapour diffusion resistance of the water vapour retarder.

5. Flanges and fittings

The example of a flanged fitting is used to demonstrate the possibilities for the minimisation of moisture ingress through air draught and water vapour diffusion.



The water vapour retarder encloses the piping insulation and is connected with the object before the fitting, i. e. must be brought down to the pipe carrying the medium. This is done to avoid the diffusion of moisture, respectively the ingress of moist air into the piping insulation caused either through leaks in the water vapour retarder of the box or through the necessity to disassemble the box for maintenance purposes.

The complicated geometry of the access box necessitates a specifically painstaking sealing. The insulation itself, in this case assembled with pipe segments, is additionally secured with adhesive.

In the relatively large cavity between fitting and insulation, under-pressure occurs as the installation starts to get cold. This under-pressure theoretically amounts at -40 °C to $0,1\text{ bar}^1$ relative to the ambient pressure. Through pressure exchange, moist air from outside flows into the cavity of the access box and condenses in the form of dew there.

This problem can be avoided by foaming the cavity or packing it with insulation material shaped-pieces – not shown in this picture.

The metallic access of the spindle constitutes an unavoidable thermal bridge. It may lead to ice on the wheel of the temperature of the medium is sufficiently low and the moisture in the ambient air high enough. This, however, does not constitute an insulation failure.

6. Summary

Moisture condensation in the insulation material and at the surface of the object must be prevented. To achieve this, the water vapour retarder must be tight against air flow and “retarding” against diffusion, and closed cell insulation materials must be used, effectively glued together.

Cold insulations have a limited life expectancy. They are unstable systems, which for physical reasons react sensitively to damages. They must be maintained regularly, which includes a routine check of sealings and interruptions.

¹ The pressure is calculated out of the mean temperature $\frac{20 + (-40)}{2} = -10\text{ °C}$

For cold insulations, it is important that:

- **closed cell insulation materials are used,**
- **joints between form-pieces are sealed,**
- **water vapour retarder is fitted air-flow-tight,**
- **water vapour retarder is glued with its entire surface to the insulation material,**
- **water vapour retarder is protected from damage,**
- **breaks in insulation are carefully sealed off.**

Temporary moisture condensation on the casing or on the water vapour retarder of the cold insulation cannot be avoided in all atmospheric conditions (see FESI Document 05).

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Literature: DIN 4140 chapter 6
 AGI Q 03 chapter 3.4
 AGI Q 112 chapter 1.3
 AGI Q 152
 VDI 2055 chapters 3.2, 3.3

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