Study on the Condensation of Upright and Inverted roof in boreal regions

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Abstract. In this paper, the theoretical checking methods of exterior–protected construction and the experience combined with engineering practice are used to analyze the condensation of upright and inverted roof in boreal regions, During the heating, according to the allowable max of humidity of heat insulating material to calculate the humidity increment of upright and inverted roof in civil thermal design specifications (GB50176-93), it can be proved that the upright and inverted roof is not satisfied with its permissible value, This roof structure will produce condensation which is the most serious in the eaves in boreal regions, thereby causing the destruction of insulation layer, however, it can be prevented and solved by controlling the indoor temperature and humidity, increasing the penetration resistance layer of water vapor and setting the air layer, meanwhile, it can also can be obtained that inverted roof has the rationality of heat and moisture transfer ,yet protective layer should be set on the insulating layer to avoid freeze-thaw damage, direct sunlight and being blown away, for the two roof structure systems, upright roof is more widely applied in the current.

Keywords: Boreal regions; Upright; Inverted; Roof; Condensation.

1. The Introduction

In the continuous improvement of the of the heat insulation property of the exterior wall and window, at the same time, increasing the heat insulation of the roof is also an important aspect of saving building energy. When designing the structure of the building roof, it needs to consider it moisture-proof [1]. The moisture-proof design of the roof is closely connected with the economy, beauty, durability, insulation and the environment quality of the roof. In the heating period of the boreal regions, because of the large temperature difference between indoor and outdoor, the air in different temperature contains the different quality of the steam, the lower temperature, the lower amount of the water vapor. So when the air temperature drops, if the water vapor content reaches a relative saturation, the excessive water would precipitate from the air and condense to the condensation water on the lower temperatures objects. This phenomenon is known as condensation [2]. The condensation phenomenon may occur on the surface of the roof and may also occur in the migration process of water vapor (that is the inside of the roof structure).

At present, many home and abroad scholars do the research about the condensation phenomenon, like the Yamada of Japan, they once analyzed in detail about the wet steam transfer process through the enclosure structure and pointed out that if the heat and the humidity movement and the mutual change of the water's gas phase, liquid phase and solid phase in the building enclosure structure exceed a certain limit, it would cause different degree of damage on insulation layer, bearing structure layer, protective material layer and the outside surface layer. If the situation is serious, it would cause disastrous consequences [3]. Some related scholars in Russia also did some researches on condensation phenomenon, and then came up with the formula of avoiding the condensation of the constructional column [4] and so on. In domestic, researching about the condensation phenomenon started later. After the reform and opening-up policy, successively, some scholars do the research in the condensation phenomenon. Such as, Tong lian zhi studied the reason and the control of the building condensation[5], Gao rong xi and Li sheng jiang studied the reason of the mustiness and the condensation of the building wall, and also put forward the means of controlling the condensation[6], Wu jian min analyzed the compare of the upright roof and inverted roof in the actual application[7], and Xu hai yan through research showed that in the application of the polystyrene bubble inverted roof, the roof would not appear condensation[8]and so on.

From the research of the above scholars, although they presented a theoretical formula to calculate the rationality of heat and moisture transfer and put forward measures to prevent condensation of exterior-protected structure, but they were not aimed at the concrete construction system in boreal regions roof to analyze the condensation and did not put forward some measures which met our country's engineering practice of preventing roof condensation. Based on this situation, this article analyzes and solves the problems above. By using theoretical formula and basing on the experience of engineering practice to analyze the reason of the question whether the roof in boreal regions would produce condensation and come up with some rationalization proposals about which roof construction system fits for our country. From the energy-saving standards and the strategy of sustainable development, especially, when we design the roof construction in the boreal regions in our country, to think about the condensation is very necessary. Because in boreal regions, the temperature difference does exist on both sides of the roof protected construction, and the steam is unequal between indoor and outdoor air. The steam pressure indoor is higher than the steam pressure outdoor, then the steam transfers from indoor to outdoor, in this process, if the temperature reaches to the dew-point temperature, the roof construction may appear condensation, and the condensation water would make material damp, reduce the insulation effect of material, also may make material mildew. To more seriously, it would generate freezing and thawing damage, thus affecting the thermal insulation and waterproof effect in boreal regions.

2. The testing methods of condensation[9]

The checking calculation of the roof condensation often uses rough analysis methods, namely under steady-state conditions, to take into pure water vapor transfer process account. That is to calculate that the indoor and outdoor temperature or humidity would not change over time which would not consider the motion of the liquid water or the heat and mass transfer.

To determine whether the inside of the retaining structure would appear condensation, follow the steps below:

According to the indoor temperature (t_i), the outdoor temperature (t_o), (unit: ^{0}c) and the relative humidity Ψ_i, Ψ_e, then to calculate the water vapor partial pressure P_i and P_e (unit: P_a) of the inside surface and the outer surface of the roof.

$$P_i = P_{s,i} \times \Psi_i \quad (1)$$

$$P_e = P_{s,e} \times \Psi_e \quad (2)$$

In these formulas, $P_{s,i}$ and $P_{s,e}$ are saturation water vapor pressures when temperatures are t_i and t_e. Strictly speaking, $P_{s,i}$ and $P_{s,e}$ are the indoor and outdoor saturated water vapor pressures. Because the water vapor permeation resistance of the roof surface is smaller than that is in roof, so we think that the indoor and outdoor saturated water vapor pressures are the same as saturated water vapor pressures of the inside surface and the outer surface of the roof.

Calculating the partial pressure of water vapor P_m (m=2, 3, 4, 5 …n) (unit: P_a) in any layer interface inside the roof, calculating as follows (the order of the material is from the indoor to the outdoor):

$$P_m = P_i - \frac{\sum_{j=1}^{m-1} H_j}{H_o}\left(P_i - P_e\right) \quad \text{(m=2, 3, 4…, n)} \quad (3)$$

In this formula, H_o is the total water vapor permeation resistance on the roof $(m^2 \cdot h \cdot p_a)/g$. Calculating from the indoor $\sum_{j=1}^{m-1} H_j$ is the sum of the water vapor permeation resistance from the first layer to the m-1 layer.

The calculating of the total water vapor permeation resistance of the roof as follows:

$$H_0 = H_1 + H_2 + H_3 + .\cdots\cdots = \frac{\delta_1}{u_1} + \frac{\delta_{21}}{u_2} + \frac{\delta_3}{u_3}\cdots\cdots \quad (4)$$

In this formula, δ_m is the layer m's thickness (unit: m). μ_m is the layer m's water vapor penetration coefficient $g/(m^2 \cdot h \cdot p_a)$. H_m Is the layer m's water vapor permeation resistance $(m^2 \cdot h \cdot p_a)/g$.

The relation of some layer's water vapor permeation resistance H_m and water vapor penetration coefficient μ_m is as follows:

$$H_m = \frac{\delta_m}{\mu_m} \quad (5)$$

Calculating the saturated water vapor pressure $P_{s,m}$ (m=1, 2, 3 ……n+1) (unit: P_a) of any layer's surface inside the roof. When m=n+1, it calculates the saturated water vapor pressure of the outside surface of the roof. In certain atmospheric pressure (standard atmospheric pressure), the saturated water vapor pressure and temperature are one-to-one correspondences. By calculating the temperature t_m (unit: ℃) on any layer's surface inside the roof, by checking the saturated water vapor table under standard atmospheric pressure with different temperatures to get that. The calculation is as follows (the order of the material is from the inside to the outside):

$$t_m = t_i - \frac{R_i + \sum_{j=1}^{m-1} R_j}{R_o}(t_i - t_e) \qquad \text{(m=1, 2, 3 …..n+1)} \quad (6)$$

In this formula, R_o is the total thermal resistance of roof (unit: $m^2 \cdot k/w$). R_i Is the heat exchange resistance of interior surface of the roof (unit: $m^2 \cdot k/w$). Generally, it values 0.11. Calculating from the indoor $\sum_{j=1}^{m} R_j$ is the sum of the thermal resistance from the first layer to the m-1 layer.

The calculation of the total thermal resistance R_o is as follows:

$$R_O = R_1 + R_2 + \cdots\cdots R_i + R_e$$
$$= \frac{\delta_1}{\mu_1} + \frac{\delta_2}{\mu_2} + \cdots\cdots R_i + R_e \quad (7)$$

In this formula, R_e is the heat exchange resistance of exterior surface of the roof (unit: $m^2 \cdot k/w$). Generally, it values 0.04. The relation of the thermal resistance R_j and the thermal conductivity λ_j of the material of the number j layer is as follows:

$$R_j = \frac{\delta_j}{\lambda_j} \quad (8)$$

In this formula, δ_j is the thickness of the number j layer (unit: m). λ_j is the thermal conductivity of the number j layer [unit: $w/(m \cdot k)$]. R_j Is the thermal resistance of the number j layer (unit: $m^2 \cdot k/w$).

Making the line P_m and the line P_s of the roof, if the line P_m and the line P_s do not intersect, the inside would not appear condensation. If the two lines intersect, the inside may appear condensation.

3. The research of the roof condensation in heating period

The analysis of the condensation of upright and inverted roof in heating period

Use the analysis theory above to analyze the condensation of upright and inverted roof in heating period in boreal regions.

Take Harbin for example, in heating period, in the calculation, the heating period is 176 days, the average temperature outdoor is -10.0℃, the average relative humidity outdoor is 66%, the temperature indoor is 18℃, the relative humidity indoor is 66%[10].

3.1 The condensation research of the upright roof

(1) Structure and material parameters [10]

The structure of the roof is: interior layer + cast-in-place reinforced concrete roof plate + aerated concrete fragments + cement screed + EPS + cement screed + petroleum asphalt waterproof layer. The materials and the parameters of each layer and the calculation results are shown in table 1.

Table1 the parameters of upright roof

Structure form	Material names and serial numbers	ρ_o kg/m3	Thickness $\delta(mm)$	Coefficient of thermal conductivity $\lambda[w/(m\cdot k)]$	Steam permeability coefficient of the material μ $10^{-4}\, g/m\cdot h\cdot p_a$	Thermal resistance $R=\frac{\delta}{\lambda}$ $m^2\cdot k/w$	Water vapor permeability resistance $H=\delta/\mu$ $(m^2\cdot h\cdot p_a)/g$
Upright roof	1 Interior layer	1600	2	0.60	0.1	0.0033	200.00
	2 Cast-in-place reinforced concrete roof	2500	120	1.74	0.158	0.069	7594.94
	3Aerated concrete fragments	700	80	0.24	0.998	0.3333	801.60
	4 Cement screed	1800	20	0.93	0.21	0.0215	952.38
	5 50mm EPS	20	50	0.042	0.162	1.19	2631.58
	6 Cement screed	1800	20	0.93	0.21	0.0215	952.38
	7 Petroleum asphalt waterproof layer	1400	4	0.27	0.075	0.0148	53333.33

Note: the roof structure to falls layer’s average thickness is taken as 80mm (i=2%), and taken the thinnest roof structure to falls of the cornice as 30mm.

(2) The calculating results

According to the theoretical formula above, we can calculate out the water vapor partial pressure and saturated vapor pressure in each layer’s interior-surface inside the upright roof shown in table 2.

Table 2 the water vapor pressure gauge of each layer of upright roof

The number of the materials inside surface in each layer of upright roof	1	2	3	4	5	6	7	8
Water vapor partial pressure (unit:P_a)	1237.5	1234.29	1112.49	1099.64	1084.37	1042.16	1026.89	171.6
Saturated water vapor pressure (unit:P_a)	1850.74	1845.44	1723.32	1226.97	1199.4	288.76	279.95	273.57

Making a distribution diagram of water vapor partial pressure P_i and saturated water vapor pressure P_s of the upright roof is shown in graph 1.

(3) The analysis of results

We can obviously find from the graph 1 that in the EPS and the number 6 layer cement screed (we do not need to analyze the condensation of roof structure 6, because the roof structure 6 can be rounded, only to analyze the condensation of the insulation layer of roof.), it would appear that the saturated water vapor pressure isles than the water vapor partial pressure. This kind of roof structure would condensate in this environment. After repeatedly calculating, where the roof structure to fall is thinner, it is easier to condensate (that is cornice), the condensation position is the exterior-surface of insulation layer and the interior-surface of waterproof layer. In retaining structure, because of the condensation and damp, the humidity increment that the insulating material generates is smaller than the allowable humidity increment. In the design standard, the allowable humidity increment stipulates Styrofoam is 15% [9], the formula to calculate the humidity increment is as follows:

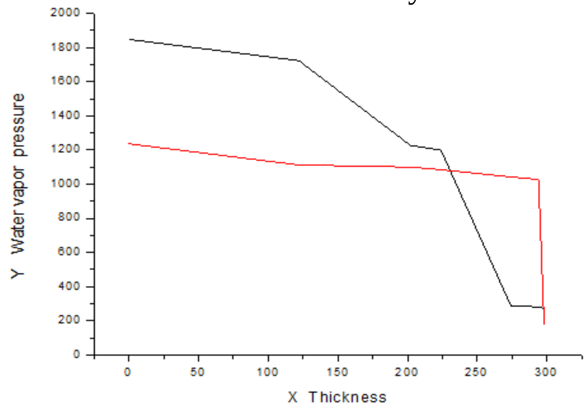

Figure 1. the distribution diagram of water vapor partial pressure of upright roof

$$\Delta w = \frac{24z}{1000\rho\delta_i}\left(\frac{p_i - p_{s,c}}{H_{0,i}} - \frac{p_{s,c} - p_e}{H_{o,e}}\right)\times 100\% \quad (9)$$

In this formula, ΔW is the weight humidity increment of the insulating material in heating period. Z is the heating period days, day. ρ Is the dry density of the insulating material. EPS plate is taken as 20kg/m^3. δ_i Is the thickness of the insulating material, m. $H_{o,i}$ is the steam permeability resistance inside the condensation layer, $(m^2 \cdot h \cdot p_a)/g$. $H_{o,e}$ Is steam permeability resistance from the condensation layer to the retaining structure exterior-surface, $(m^2 \cdot h \cdot p_a)/g$. P_i is the water vapor partial pressure in the indoor air, P_a. P_e is the water vapor partial pressure in the outdoor air, P_a. $P_{s,c}$ is the saturated water vapor partial pressure in the condensation layer, P_a.

Calculating the temperature increment of the EPS is:

$$\Delta w = \frac{24z}{1000\rho\delta_i}\left(\frac{p_i - p_{s,c}}{H_{0,i}} - \frac{p_{s,c} - p_e}{H_{o,e}}\right)\times 100\%$$
$$= 31.99\%$$

This value goes far beyond the design value 15%.

3.2 The analysis of condensation of the structural system of inverted roof

Table3 the material's performance parameters of inverted roof

Structure form	Material names and serial numbers	ρ_0 kg/m3	Thickness $\delta(mm)$	Coefficient of thermal conductivity $\lambda[w/(m\cdot k)]$	Steam permeability coefficient of the material μ $10^{-4}\ g/m\cdot h\cdot p_a$	Thermal resistance $R=\frac{\delta}{\lambda}$ $m^2\cdot k/w$	Water vapor permeability resistance $H=\delta/\mu$ $(m^2\cdot h\cdot p_a)/g$
Inverted roof	1 Interior layer	1600	2	0.60	0.1	0.0033	200.00
	2Cast-in-place reinforced concrete roof	2500	120	1.74	0.158	0.069	7594.94
	3 Aerated concrete fragments	700	80	0.24	0.998	0.3333	801.60
	4 Cement screed	1800	20	0.93	0.21	0.0215	952.38
	5 Petroleum asphalt waterproof layer	1400	4	0.27	0.075	0.0148	53333.33
	6 40mm XPS	30	40	0.03	0.234	1.3333	1709.40
	7 Cement screed	1800	20	0.93	0.21	0.0215	952.38

Note: the roof structure to falls layer's average thickness is taken as 80mm (i=2%), and taken the thinnest roof structure to falls of the cornice as 30mm.

(1) Structure and material parameters [10]

The structure of the roof is: interior layer + cast-in-place reinforced concrete roof plate + aerated concrete fragments + cement screed + petroleum asphalt waterproof layer + 40 XPS + cement screed. The materials and the parameters of each layer and the calculation results are shown in table 3.

(2) The calculating results

According to the theoretical formula above, we can calculate out the water vapor partial pressure and saturated vapor pressure in each layer's interior-surface inside the inverted roof shown in table 4.

Table4 the water vapor pressure gauge of each layer of inverted roof

The number of the materials inside surface in each layer of inverted roof	1	2	3	4	5	6	7	8
Water vapor partial pressure (unit:P_a)	1237.5	1234.25	1110.74	1097.70	1082.21	214.89	187.09	171.6
Saturated water vapor pressure (unit: P_a)	1866.2	1860.2	1746.8	1275.6	1249.5	1240.7	280.76	273.04

Making a distribution diagram of water vapor partial pressure P_i and saturated water vapor pressure P_s of inverted roof is shown in graph 2.

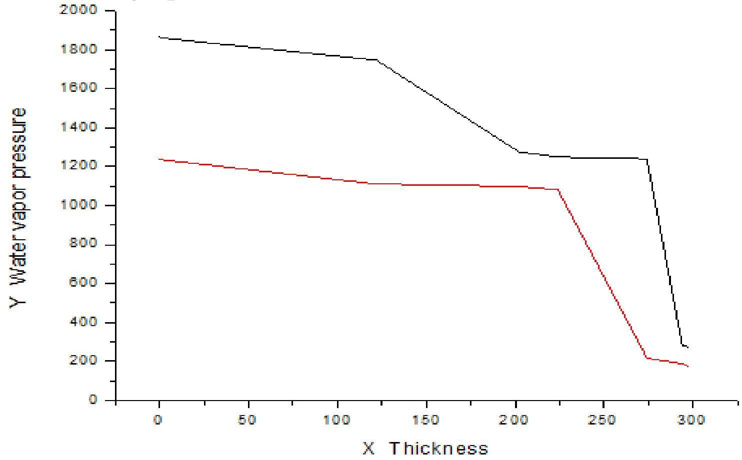

Figure 2. the distribution diagram of water vapor partial pressure of inverted roof

(3) The analysis of results

We can find from the graph 2 that in the same place of thickness of inverted roof's structural system, the water vapor partial pressure is lower than saturated water vapor pressure. So this kind of insulating and waterproof structural system of inverted roof would not condensate in this environment.

3.3 The comparative analysis and recommendations for improvement to the two roof structures' condensation results

In the heating period in North, for the structural system of upright and inverted roof, the inverted roof has the rationality of heat and humidity transfer, because the waterproof layer makes the water vapor difficult to enter the insulation layer. But because the insulation layer is on the waterproof layer of the inverted roof, the environment of the insulation layer is worse that any other ordinary layer. So it is essential to set a concrete cover on the roof so as the insulation layer could be protected by freeze-thaw damage and directly weathered. Once the United States Army cold regions research and engineering laboratory (CRREL) had did research for years on inverted roof with which they once envisaged obtaining United States patent, but in 1985, this patent terminated [11]. Especially in boreal regions in our country, the insulation layer is easy to get damp, so the inverted roof is difficult to popularize and apply in our country. Although the upright roof structure would condensate and the condensation would generate the humidity increment of the insulating material higher than the design allowable value of GB50176-93. Therefore, when using the upright roof in north regions, it should make the checking calculation of condensation. From the architecture energy-saving standards and the strategy of sustainable development, using the below methods can reduce and prevent the condensation of upright roof, meanwhile, the upright roof is easy to popularize and apply.

Set a steam layer under the insulation layer. If you worry about the aging of the material of steam layer would affect the performance of the insulation layer, you can build a ventilation layer on the insulation layer which is the same as setting a permeable layer on the insulation [2].

Make the indoor relative humidity of the air at a reasonable range. You cannot leave the indoor humidity too high and control the humidity source [6]. Such as, attention of moisture from toilet and kitchen facilities avoids getting into another room. In some conditional regions, you should install exhaust window to make the moisture output quickly, and you can take air-conditioner to output the moisture or the dehumidifier to reduce the relative humidity indoor.

Control the temperature difference between inside and outside the roof. In the heating period in boreal regions, try to keep the indoor be constant temperature [6]. Because according to the theoretical formula and engineering practical experience we can get that after reducing the temperature indoor, the condensation of retaining structure would be worse. So in conditional heating house, it should try the best to use continued heating or to reduce the heating space time to cover the heating instability of roof. For example, in some regions with environmental requirements, they use infrared electric heating film heating system to continuously heat. In some intensively heating residential quarters, they also can use hot water net to intensively heat and so on.

In boreal regions, when they do construction to the upright roof, they should deeply communicate with the construction team and tell the technology to them, let them strictly carry out the operation of waterproof insulation technology, use eligible material, don't lay insulating material under damp environment, strictly test the moisture percentage of insulating material. If the place to lay the insulating material is not easy to dry, they can set kicker port under waterproof layer which is easy to output the moisture and reduce the moisture sources [6]

In conditional boreal regions, the roof interior-surface brushes a waterproof steam layer and sets ceiling which can be a decoration. Meanwhile, the waterproof steam layer can prevent condensation of roof. Another big advantage of doing this is that there exists air space between the ceiling and the interior-surface of roof, so we can adequately use this air space to reduce the steam from air across the roof structure layer, such as the usage of air-conditional dehumidification, dehumidifier, and exhauster and so on.

All the above advices, we can synthetically consider when doing the roof structure system design. But the author recommend give the first priority to the number 5 advice. Because after the development of our country's economy, many buildings use ceiling to beauty the building, so we can set steam layer in the interior-surface of the roof. If the material of steam layer ages, it is convenient to replace the material to prevent the mildew and keep a healthy environment indoor.

4. Conclusions

Through the analysis of two insulation waterproof construction system of roof in our country's boreal regions, the constructed level of inverted roof has the rationality of heat and humidity transfer. While the upright roof does not have it, but from the architecture energy-saving standards and the strategy of sustainable development, inverted roof is difficult to popularize and apply, so the author recommend to use upright roof for it is efficient to prevent the condensation of roof (especially the number 5 advice), and the upright roof has many advantages, such as, convenient to operate, high guarantee, lower repair cost, and simple to deal with leakage and so on.

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