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Heiselberg, Per Kvols

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Evaporative Cooling of Walls For High Performance Buildings in Hot Climates

Burhan YÖRÜK^{#1}, Ahmet ARISOY^{#2}

[#]*Faculty of Mechanical Engineering, Istanbul Technical University
İnönü Caddesi, No. 65 Beyoğlu / Istanbul , TURKEY*

¹byoruk@itu.edu.tr

²arisoyah@itu.edu.tr

Abstract

When a cooling weighted climate is considered, evaporative cooling of outer walls can be a very valuable tool reducing cooling loads from outer skin of the buildings. This layer can be applied on the inside of the wall and this system can also be used in dry state during the winter reducing the heating loads without evaporation.

Thermal performance of such a building envelope with such a heat exchanging layer in Mediterranean region has been analyzed through energy simulation software EnergyPlus and through a specially developed model. Annual cooling energy demand has been evaluated. Simulation results show that this system is more successful comparing the thermal insulation in Mediterranean climate.

Keywords - Energy efficient buildings, Evaporative cooling, Mediterranean Climate

1. Introduction

Energy consumption in residential and commercial buildings corresponds 40% of the total energy consumption in 28 EU countries [1]. So, reduction of this value is an important goal for European Union to reduce its energy dependency. Energy Performance Buildings Directive (EPBD) is the most important action that has taken against this issue. According to this directive, by the end of 2018 every public building has to be compatible with nearly zero energy standards and by the end of 2020 all new buildings have to be nearly zero energy [2]. The definition of energy efficiency measures and packages are strictly related to the climate, considering both temperature and humidity. Therefore, for Mediterranean climate, specific solutions are certainly required.

Behavior of outer walls play an important role on heat gains and heat losses of the building. Thermal insulation of walls is known as an important measure to reduce static heat loss of buildings for cold and mild climates. However, increasing thermal insulation thickness plays a reverse effect on heat gains in dynamically changing hot climates [3]. Evaporative cooling of outer walls can be a very valuable tool reducing cooling loads from outer skin of the buildings in such climates.

Evaporative cooling has gained importance in recent years to reduce the energy demand in buildings [4-9]. Due to developments in natural cooling,

this old technic has been integrated to the modern technology and very successful applications have been emerging everywhere in the World. These technics can be divided into two as direct evaporative cooling and indirect evaporative cooling.

Direct evaporative cooling of buildings can be achieved by packaged evaporative cooling units. This can be considered as an active system. The other solution is that evaporative system can be an integrated part of the building itself and these systems are defined as passive systems. Passive systems are usually part of the building outer skin [4]. In case of passive evaporative cooled walls, porous ceramic building elements can carry water by the force of capillary. Porous material applications are based on using porous material on the outer surface of the buildings [6]. This material will hold the humidity and store the water on the wall. When sun is effective evaporation of this water will cool down the wall and this will decrease the heat gain from the wall. This is one of the effective method to reducing the cooling load for hot and rainy climates [7]. Another effective indirect application is covering outer surface of the wall by a water absorbing film. This can be applied to the roofs also. TiO_2 coverings have been developed for this purpose [5].

An evaporative layer to be applied on the inner surfaces of outer walls has been designed and proposed in this study to reduce the cooling load of buildings in Mediterranean region. This can be considered as a new approach. A building has been considered in Mediterranean region as the case study. Considered building has an air conditioning system that keeps indoor temperatures at the required level. The target is reducing cooling loads from outer walls for energy conservation. The proposed heat absorbing layer basically consists of two plate with a gap between them and it is applied on the inner side of the outer walls. Proposed system has to be coupled with the present ventilation system of the building. Cooling inner surfaces of the outer walls reduces heat gain from the outer walls and more importantly increases the thermal comfort in summer conditions.

This case study has been conducted to design and to analyze this proposed system. A sample building in İzmir has been considered and this proposed system has been designed and applied to this building. A simple model has been developed to design the system. Performance of the system has been investigated by the help of a building simulation software. It has been shown that this system is more successful comparing the thermal insulation in Mediterranean climate. Depending on the design parameters the peak heat gain through the outer walls can be compensated by the system without any additional insulation layer. Even a reversed heat transfer (heat loss from indoor) can be achieved. This layer is also effective during the winter conditions. In winter season, the layer is used in dry state and it reduces the heat losses by increasing the inner wall temperatures. A feasibility study has also been carried out and simple payback times have been calculated.

2. Methodology

A standard building (compatible with TS 825 [10] Turkish standard for thermal insulation requirements for buildings) in Izmir is considered as the reference case (Fig.1) in this study. İzmir is selected as the representative of the Mediterranean climate.

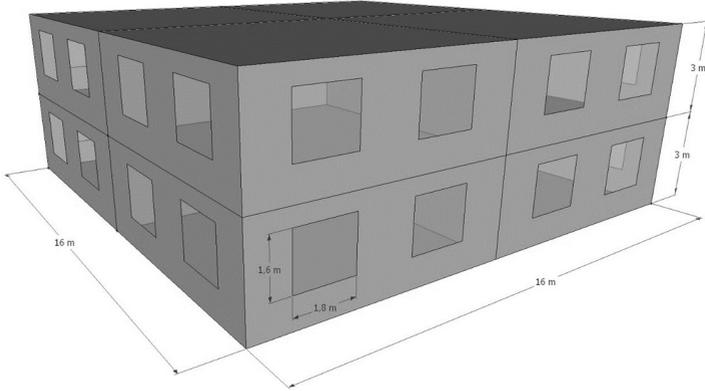


Fig. 1 3D model and dimensions of sample building

Building is considered as 2 story residential house with a total of 512 m² floor area. Total window area to external wall ratio is 24%. 5 cm thick thermal insulation has been applied to external walls.

This study is limited only with energy performance improvements which are based on enhancements of building envelope, and is only focused on passive measures.

Roof, ceiling and floor heat gains/losses have not been taken into consideration. Thus, all the heat loss and gain occurs through walls and windows, which are the main subjects for this study. Internal heat loads have also not been considered. It is assumed that there is a HVAC system which controls indoor temperatures ideally. Cooling set point temperature is 24°C all day long for summer period. Heating set point temperature is 22°C during the winter time.

3. Annual Cooling and Heating Energy Demands of the Building

Annual cooling and heating energy demands have been evaluated based on hourly analysis using energy simulation software EnergyPlus. Monthly heating energy demands for 5 cm insulation and cooling energy demands for no insulation and 5 cm thick insulation are presented in Table 1. Annual heating energy requirement for this building is calculated as 6127 kWh_{heat} and annual cooling energy demand is 34162 kWh_{heat} in case of 5 cm thick insulation.

Table 1. Monthly and annually heating and cooling energy requirements for the building from outer walls

	Heating Energy Demand [kWh _{heat}] (5cm Insulation)	Cooling Energy Demand [kWh _{heat}] (5cm Insulation)	Cooling Energy Demand [kWh _{heat}] (No Insulation)
January	1577	280	235
February	1284	411	349
March	559	1136	925
April	133	1616	1236
May	1	4197	4014
June	0	5760	6123
July	0	6289	6826
August	0	6352	6819
September	0	5205	5337
October	39	2156	1846
November	749	619	559
December	1785	141	120
TOTAL	6127	34162	34389

It is seen that January, February, November and December could be considered as heating season and remaining months could be considered as cooling season for Izmir. Cooling energy demand is approximately 6 times larger than heating. So, any cooling related energy performance improvements for Izmir (and for Mediterranean region) will have a significant effect improving total energy performance of the building. In no insulation case cooling energy demand is less than comparing 5 cm insulated wall case except 4 summer months and total cooling loads for these two cases almost the same. Insulation of walls doesn't create any difference in terms of total yearly cooling loads in Mediterranean climate. Increasing insulation thickness is not a good strategy reducing the cooling energy demand especially for intermediate seasons and new strategies should be developed for outer skin of the buildings in Mediterranean climate.

4. Evaporative Cooling Layer Modules

Considering this fact, it is proposed a novel evaporative cooling approach for the outer walls in hot and dry climates and also in Mediterranean climate to maximize the benefits. This approach is based on a modular evaporative layer to be applied on the inner surface of the outer walls. This layer to be attached to the wall surfaces tightly by screws and it should be leak-proof. The drawing of a module is seen in (Fig.2). These modules can be connected to each other and all the outer wall inner surfaces can be covered with these elements. Frame of the module is steel and the outer panels of the module can be either plastic or sheet steel. There is a porous pad attached to the back side

panel of the module and there is a gap for air flow between this pad and the front side panel of the module. Pad is made of synthetic fibers and it is wetted by the water dripping nozzles at the top. Gap dimensions and air flow rate have been designed by the help of the developed model. Room air is introduced to the gap from bottom of the designed element and this air picks up the evaporated water from wetted pad. Collected air at the top of the gap is exhausted to the outdoor by the help of a fan. This air circulation system can also be part of the mechanical ventilation system of the building.

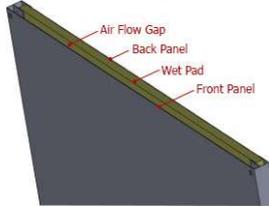


Fig. 2 Drawing of the designed evaporative module

5. Performance of the Modules for the Sample Building

Heat and mass transfer processes in the evaporative layer have been modelled for design purposes. Modelled system is given in the (Fig.3) schematically.

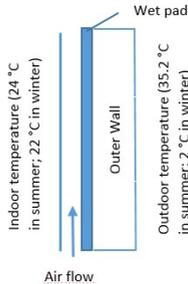


Fig. 3 Schematic drawing of the model

Heat and mass conservation equations have been written for the flowing air in the gap. For design purposes steady state has been assumed as the first approximation. In summer conditions heat is transferred from the outer wall to the flowing air through the wet pad and also a heat transfer occurs between indoor air and the flowing air in the gap. There is a vapor transfer from wet pad to the flowing air and necessary heat for evaporation is supplied both from flowing air and from outer wall. Following equations can be written:

Energy balance for flowing air;

$$VA\rho c_p dT = hL(T - T_s)dx + h_i L(T - T_i)dx \quad (1)$$

Water vapor balance for flowing air;

$$VA\rho dw = h_m L(w_s - w)dx \quad (2)$$

Energy balance for liquid water film;

$$hL(T - T_s) + \frac{k}{\delta_w}(T_a - T_s) = h_m H_{fg}(w_s - w) \quad (3)$$

Energy balance on the outer surface of the wall;

$$h_d(T_a - T_o) + \frac{k}{\delta_w}(T_a - T_s) = \alpha q''_{sol} \quad (4)$$

Relationship between saturation pressure and temperature;

$$w_s = 0.0046 \exp(0.0588T_s) \quad (5)$$

In these equations; A: air flow cross section in module (m²), h: convective heat transfer coefficient (W/m²K), h_m: convective mass transfer coefficient (kg/m²s), H_{fg}: heat of evaporation (J/kg), L: width of the module (m), T: flowing air temperature (°C), T_a: wall surface temp. (°C), T_o and T_i: outdoor and indoor temperatures (°C), T_s: saturation temperature (°C), w: moisture ratio of air (kg_{mois}/kg_{air}), w_s: saturated moisture ratio of air (kg_{mois}/kg_{air}), V: air velocity (m/s), q''_{sol}: Solar radiation (W/m²), ρ: air density (kg/m³), δ_w: wall thickness (m).

Equations have been solved by using MatLab solver. Two different cases have been studied as wet pad in summer and dry pad in winter season. Temperature and humidity variations have been solved for these cases. As the result of parametric investigations; optimized dimensions, air flow rates and water feeding rates have been determined. At the same time performance of the proposed system have been evaluated.

Only 1 m width of the layer has been studied. Height of the layer is 3 m and the optimized air flow clearance is 0.01 m and optimized air flow velocity is 1 m/s. Indoor air temperature (and the air temperature at the entrance of the layer) is 24 °C and the humidity ratio of air is 0.0093 kg/kg for summer season. This humidity ratio corresponds to 50% relative humidity. Solar radiation on the outer surface of the wall is considered and the corresponding peak surface temperature is calculated as 40 °C which is higher than the outdoor air temperature.

If no thermal insulation or no evaporative layer has been considered, for the bare outer wall, steady state inside surface temperature will be 30.7 °C in summer design conditions and the total heat gain from the 1x3 m² bare outer wall will be 140 W. Same inner surface temperature for bare wall will be 13.7

°C in winter design conditions and heat loss value will be 175 W. These values are to be considered as the base case and different cases will be compared with these values to evaluate the performances.

5a. Case A: Evaporative Wet Layer Performance in Summer

In Case-A pad is kept wet by supplying water from top. Flowing air temperature variation along the height of the layer is given in Fig.4. In this case pad is wet and evaporation occurs. With the help of evaporation, inside wall surface temperatures can be kept below the room temperature. This causes a reversed heat flow and creates a cooling effect. These low inner surface temperatures also help improving comfort conditions due to radiative heat transfer between wall and the occupants. Leaving air temperature at the top of the layer is 20.9 °C which is 3 °C lower than the room air. Meanwhile specific humidity increases from 9.3 g/kg to 12.3 g/kg in outgoing air. Leaving air specific humidity corresponds to approximately 80% relative humidity value. This humid and cool air can be used in a conventional heat recovery unit to reduce the temperature of incoming hot ventilation air. In wet case proposed evaporative layer can be considered as an additional cooling element.

Heat flow rate variation from the room along the height of the layer is given in Fig.5. Total additional cooling from this 1x3m layer is -15.2 W. However, without applying this evaporative layer, heat gain from same bare surface was 140 W. This additional cooling effect cannot be realized by thermal insulation only. This performance of proposed layer has been evaluated for steady state design conditions. When dynamic behaviour of outer wall is considered performance of this layer should be much better.

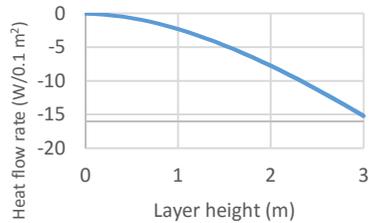
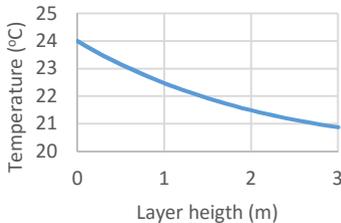


Fig. 4 Flowing air temperature variation along the height of air gap in summer wet case

Fig.5 Heat flow variation along the height of air gap in summer wet case

5b. Case B: Dry Layer Performance in Winter (No Evaporation)

Heat loss should be reduced from the outer walls in winter. The common solution for this heat conservation is applying thick thermal insulation to the outer walls. Without any thermal insulation, inner surface temperature of 1m

wide and 3 m high bare wall will be 13.7 °C in steady winter design conditions and heat loss value from this part will be 175 W.

In (Case-B) pad is kept dry but the air flow continues. This regime can be used during the winter. The calculated flowing air temperature variation along the height of the layer for this case is given in Fig.6. It is assumed that indoor temperature is kept at 22 °C by the heating system. Inside wall surface temperatures can be increased by the flowing warm room air in the layer gap. These elevated inner surface temperatures help improving comfort conditions and due to the reduced temperature difference between wall and the room heat loss is also reduced. The temperature of leaving air is 20.3 °C and the mean temperature difference between room and the layer is about 1 °C. In winter case this proposed dry layer again can be considered as a heat recovery unit.

Heat loss variation from the wall along the height of the layer is given in Fig.7. Total heat loss from this 1m wide, 3m high layer is 7 W. However, without applying this dry layer, heat loss from same bare wall was 175 W. The reduction is too big again and same reduction can be obtained only by 7.5 cm thick thermal insulation.

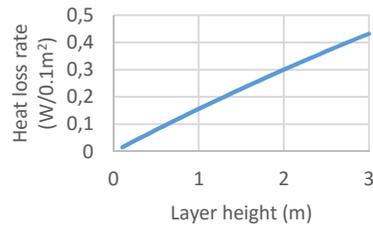
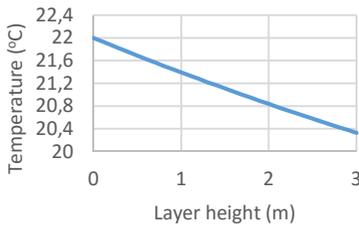


Fig.6 Flowing air temperature variation along the height of air gap in winter dry case

Fig.7 Heat loss variation along the height of air gap in winter dry case

6. Annual Performance of the Proposed Layer

Monthly average outdoor temperatures and solar radiations on vertical walls for 4 main directions are given in TS 825 [10] for İzmir (Mediterranean Region) climate. Using this data and the above mentioned formulation, monthly steady heat gain/loss values of the building have been calculated. All the outer walls have been considered and averaged monthly heat gains (and losses) have been calculated for three different cases, namely bare walls without insulation, thermally insulated walls and walls covered with proposed evaporative layer. Evaporative layer will be operated dry during the 6 winter months and will be operated wet during the 6 summer months. Indoor set temperature 22 °C for 4 months (January, February, November and December) and 24 °C rest of the year. Results are given in Table 2. Positive sign indicates either heating or cooling load for air conditioning equipment. Minus sign indicates additional cooling load reduction from the air conditioning equipment. When all internal and external loads are considered cooling is

required during the 8 months of the year. During the cooling period heat loss to evaporative layer help reducing the cooling load of the air conditioning system.

Table 2. Total monthly heat lost/gain from south facing walls (kWh)

Cases →	Isolated Wall		Bare Wall		Evap. Layer Covered Wall	
	Heating Load	Cooling Load	Heating Load	Cooling Load	Heating Load	Cooling Load
January	1499		5436		206	
February	1296		4701		178	
March	1077		3907		148	
April		-384		-1392		-1131
May		526		1907		-1115
June		1301		4717		-1102
July		1613		5848		-1096
August		1383		5015		-1100
September		641		2325		-1113
October	224		811		31	
November	867		3143		119	
December	1427		5175		196	
Annual	6390	5080	23173	18420	879	-6657
Total Annual	11470		41592		-5778	

In according to these results, applying evaporative layer is the best solution for İzmir. Thermal insulation reduces loads from 41592 kWh to 11470 kWh annually. Saving is about 30122 kWh annually. However, in case of proposed evaporative layer, saving is higher comparing the thermal insulation and it is about 47370 kWh annually.

7. Cost Analysis and Simple Payback Time Considerations

Cost of single module including connection and sealing elements is 68.4 TL. Considering total wall area, 384 modules are required, so total cost of the modules is 23458 TL. Other elements of the system are fan, pipes and ducts. Total cost considering these elements is 32550 TL. Operational costs are water and electricity and total cost of these two items have been calculated as 410 TL/a. Considering averaged COP value of the air conditioning equipment and the cost of electricity and the annual 47370 kWh heat saving value, annual energy cost saving is 6316 TL. From these figures and from end value of the system, simple payback time is approximately 4.5 years.

8. Conclusions

Evaporative layer to be applied inside surfaces of outer walls in Mediterranean climate is a novel approach. This novel element has been designed and its performance has been investigated in this study.

Simulation results indicate that this layer prevents heat gain from outer walls and provides additional cooling during summer period in İzmir conditions. This layer can also be used in winter conditions without evaporation. Stopping water feeding and continuing air flowing heat losses can be reduced in winter conditions.

The other benefit of this layer is improving thermal comfort conditions of the indoor environment. This layer decreases wall surface temperatures in summer and increases them in winter. This creates better comfort conditions in rooms. Indoor temperature set value can be increased in summer and decreased in winter for the same comfort level.

It has been shown that evaporative layer is better solution for İzmir comparing the thermal insulation. Thermal insulation reduces loads from 41592 kWh to 11470 kWh, saving is about 30122 kWh annually. However, in case of the proposed evaporative layer, saving is higher than the thermal insulation and it is about 47370 kWh annually. Cost of the system seems reasonable. Simple pay back calculations indicate that payback time is approximately 4.5 years.

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