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Two-Stage System for Utilization of Renewable Solar Energy in Modern Building Facade Technology

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Abstract. We research a technical solution for utilization of solar energy in modern buildings with double-skin facades. The solution involves thermal conditioning of cold outdoor air in the physical cavity of the double-skin facade and utilizing the warmed up air as primary air for an air heat pump. The system for utilization of solar energy consists of two stages. The 1st stage involves transformation of the short-wave solar radiation to the long-wave heat radiation in the double-skin facade. This contributes to the reduction of heat losses from conditioned rooms because of the lower temperature difference between the rooms and the cavity. In the 2nd stage the thermally conditioned air is fed in the inlet of the air heat pump during heating season. Computer simulations performed for a cavity of a 4-storey double-skin transparent facade have shown that both the intensity of solar radiation and the air flow through the cavity significantly influence the air temperature at the outlet from the cavity. The air temperature rise in the cavity was ranging from 3.7 K for the solar radiation of 150 W/m^2 and the airflow of 200 m^3/min, up to almost 23.0 K for the solar radiation of 600 W/m^2 and the airflow of 50 m^3/min. Even at the least favourable climate conditions such increase in temperature of the primary air leads to a considerable improvement of the performance of the heat pump.

1. Introduction

The ancient Greeks believed that the universe is made up of four elements: fire, earth, air, and water. They would be surprised that the last three elements are being increasingly used as renewable energy sources for heating and cooling.

Water, if not affected by external forces, flows from top to bottom, that is, in the direction of gravity. Likewise, the heat spreads in the direction of temperature gradient. If we supply water with energy, for example by a circulating pump, we can move it against the direction of gravity. In this aspect, the principle of heat pump is similar to circulating pumps. Heat from a cold body never passes spontaneously to a warmer body. However, if we supply external energy, in case of heat pumps it is the electricity to drive the compressor, we can extract thermal energy even from a relatively cold body.

The concept of heat pumps is based on the transformation of low-potential heat to a higher thermal potential. Especially using heat pumps with air as the primary energy source can be profitable, because the investments do not comprise the costs of collectors, geothermal wells, etc. Unlike for other natural energy sources based on soil and water, the performance of air heat pumps is directly proportional to the outside temperature. When the outdoor temperature is lowest, the space heating demand is highest and the heat pump works with the lowest coefficient of performance (COP). This is an important limitation of air heat pumps as compared to ground and water heat pumps. Their low performance has to be compensated by a supplementary heat source, often an electric boiler.

Fig. 1 shows an example of the relationship between the performance of an air heat pump and the outdoor temperature. Several outdoor air temperatures should be noted:

- at optimal temperature opt. $\theta_{ae} \geq +7$ºC, the performance of the heat pump is at its maximum,
- at effective temperature effect. $\theta_{ae} \geq +1$ºC, the performance reaches about 80 % of the maximum,
- at critical temperature crit. $\theta_{ae} \approx -10$ºC, the heat pump alone usually cannot cover the heating demand and a supplementary heat source, e.g. an electric boiler, comes into operation.

In the present study we address this disadvantage of air heat pumps by proposing a solution where the outdoor air is thermally conditioned in the cavity of a double-skin facade and subsequently used as primary air for a heat pump. It is expected that the temperature of the air in the facade increases due to solar radiation, which should result in better COP. We aim at answering the question: Can using thermally conditioned air from the cavity of a double-skin facade improve performance of air heat pumps and, if yes, to what extent?

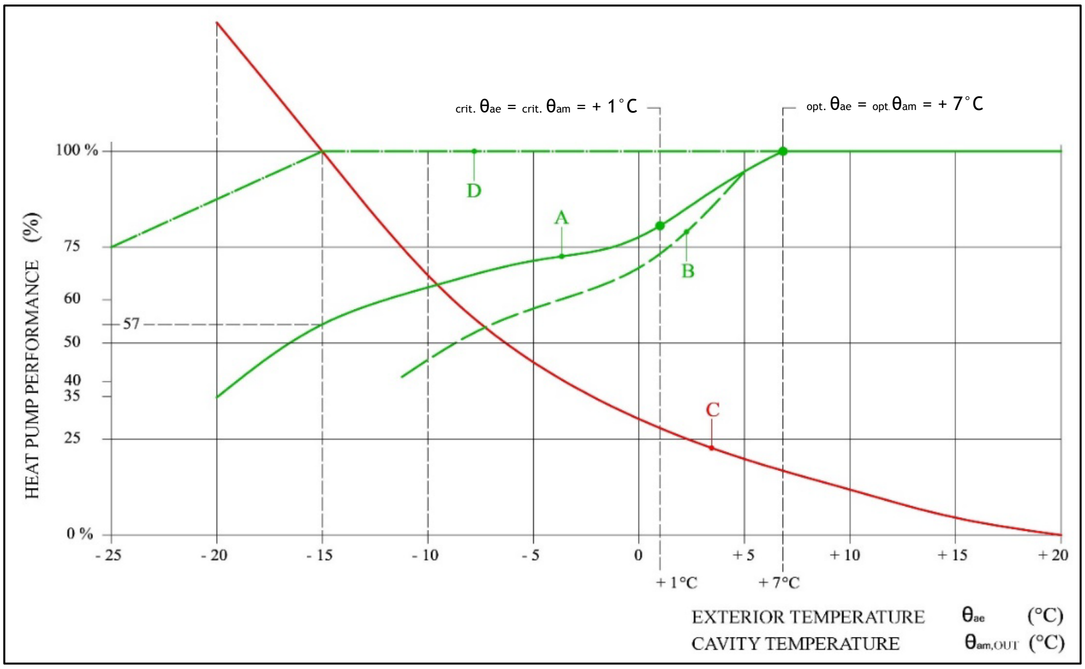

Figure 1. Example of relationship between performance of air/water heat pump and primary air temperature at heat pump inlet, θ_{ae} (ºC)
Key: A – performance of inverter heat pump with continuous output control, B – performance of heat pump with ON/OFF control (without inverter), C – energy demand for heating, D – attempts to develop new heat pump technologies.

2. Concept of the two-stage system for utilization of solar energy

The proposed technical solution involves thermal conditioning of the fresh outdoor air in a cavity and feeding the warm air in the heat pump inlet (Fig. 2). The two stages of the system for utilization of solar energy are:

(1) The 1st stage involves transformation of the short-wave solar radiation to the long-wave heat radiation in the double-skin facade. This reduces heat losses from conditioned rooms because of the lower temperature gradient between the conditioned rooms and the outdoor environment – in this case the cavity of the double-skin facade. The warmed up air can be also used for ventilation of the building.

(2) In the 2nd stage the thermally conditioned air is transported upwards because of the temperature gradient that occurs in the cavity (Fig. 2). The warmed up air is collected and fed in the inlet of the heat pump during heating season. Alternatively, the air can be exhausted through the revolving flap in case that no heating is needed such as, e.g., in summer.

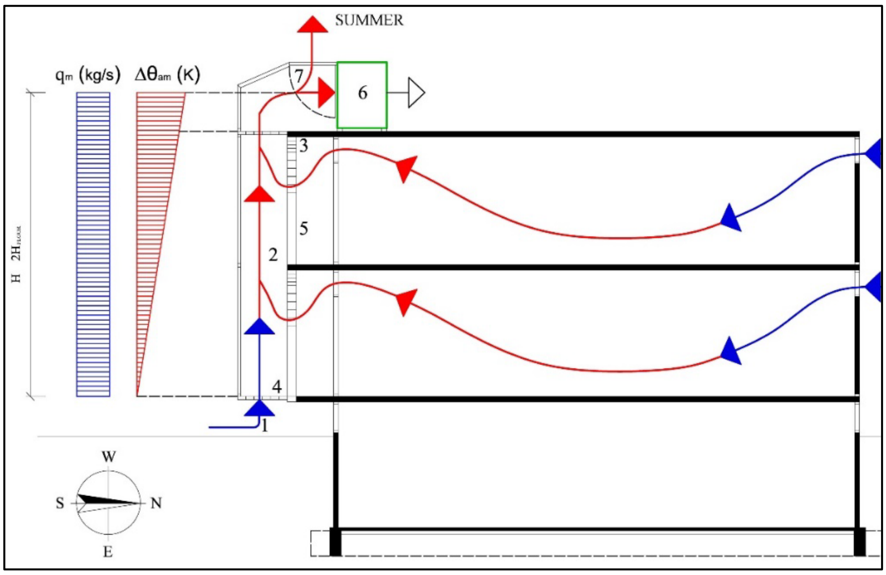

Figure 2. Utilization of thermally conditioned air from the cavity – a glazed space consisting of two levels with the effective height $H \approx 2\ H_{FLOOR}$
Key: 1-inlet to the cavity, 2-cavity, 3-shading, 4-inlet grill, 5-railing, 6-heat pump fed with thermally conditioned air from the cavity, 7-revolving flap (regime winter – summer).

It is expected that the combination of air heat pump with the transparent cavity offers different, more favourable operating modes. Using warmer air as the primary medium influences operating conditions of the heat pump as follows:

- Space heating mode = higher temperature of the primary air enhances the output of the heat pump because of the increased COP. Previous long-term measurements have shown that an increase in the inlet temperature of primary air by 1 °C improves the heat pump efficiency by about 2 %. Thus, an increase in air temperature in the transparent double-skin facade by 10 °C would mean a rise of heat pump efficiency by 20 %. Another positive effect of the higher air temperature is the reduced occurrence of air temperatures in the range of 0 to + 5 °C. Within this range problems with freezing moisture on the evaporator frequently occur. Additional energy is then needed to remove the frost. Over a typical year in Bratislava (Slovakia), there are about 60 days with the outdoor temperature between 0 and + 5 °C. After the air is thermally conditioned in the transparent cavity, the number of such days is reduced to about 20. This greatly reduces the amount of heat needed to defrost the evaporator. To maximize the heat transfer from air to water it is preferable to use a low-temperature space heating system.
- Space cooling mode = when using a heat pump with reversible flow (Fig. 3.B), the use of a high temperature cooling system with capillary mats is preferable. The combination of capillary mats with the heat pump results in a highly efficient cooling system. This improves the profitability of an otherwise expensive system with capillary mats.

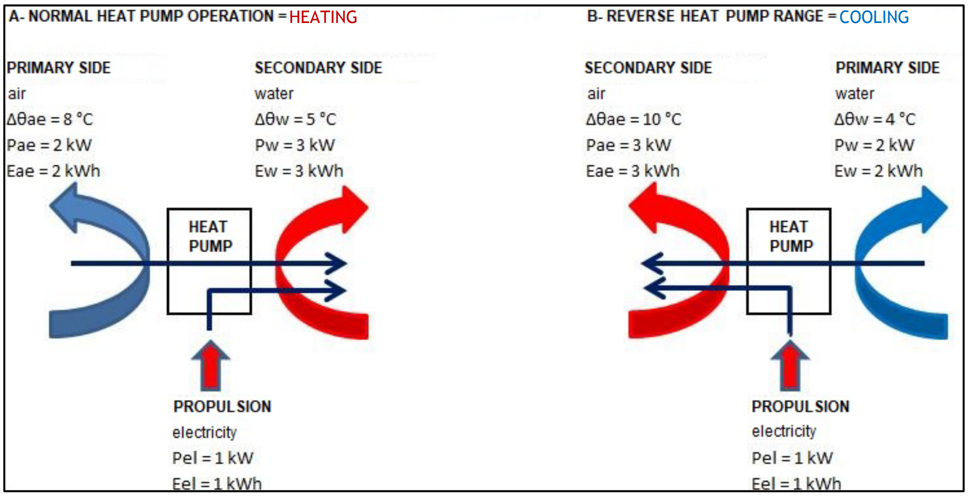

Figure 3. Heat / cool transformation by air / water heat pump
A – space heating, ventilation and domestic hot water, B – space cooling and ventilation, $\Delta\theta_{ae}$ – temperature difference on the primary side of the heat pump, $\Delta\theta_{w}$ – temperature difference on the secondary side of the heat pump, P – power input / output (kW), E – energy (kWh).

- Domestic hot water (DHW) = similar to space heating, in winter it is possible to take advantage of the combination of transparent cavity and heat pump. As the consumption of DHW is approximately constant throughout the year, the use of cavity is especially efficient during transition periods and in summer. To increase operation efficiency, it is preferable to use DHW storage tanks to eliminate the negative effect of fluctuation of air temperature in the cavity.
- Ventilation / space cooling / DHW = this mode of operation is possible with air / air heat pumps during summer and transition periods. The heat from the primary air is transferred to the heat pump circuit as it passes through the evaporator. This heat is used to heat up DHW. The cooled air after evaporator can be subsequently used for space cooling or to cool down ventilation air.

3. Verification of the concept by mathematical modelling and computer simulations

The present results refer to the operation of an air / water heat pump during heating season. Our goal is to increase the temperature in the double-skin transparent facade to attain as high an air temperature at the outlet from the cavity as possible. Two paths are considered to attain this goal:

a) reduce the air flow rate q_v (m^3/s) through the cavity,
b) increase the effective height of the physical cavity, e.g. $H = n.H_{storey}$ (m).

3.1. Model of the double-skin transparent façade

We have chosen a double-skin transparent facade with the thickness of the cavity of 800 mm and the length of a section of the façade 6 x 1250 mm = 7500 mm. This allows us to achieve the relatively high air flow needed for the heat pump (50 to 200 m^3/min). The height of the section corresponds to 4 storeys (H_{storey} = 3450 mm), as shown in Fig. 4.

The outer glazing of the double-skin façade, which influences the energy gains of the facade most significantly, is modelled as a simple dot-anchored hardened tempered glass ESG HST Float blank with the thickness of 12 mm, reflectivity R_E = 6 %, absorption A_E = 34 %, permeability T_E = 60 %, total solar energy transmittance g = 70 %, and heat transmission coefficient U_g = 5.5 W/(m^2.K).

The transparent part of the inner wall of the double-skin transparent facade consists of aluminium windows with frame profiles Schüco series AWS 90.SI ($U_f \geq$ 0.7 W/(m^2.K)) and low emission insulating triple glazing with reflectivity R_E = 33 %, absorption A_E = 20 %, permeability T_E = 47 %, total solar energy transmittance g = 45 %, and heat transmission coefficient U_g = 0.6 W/(m^2.K).

The opaque parapet of the inner wall of the double-skin transparent facade is composed of: (1) interior lime-cement plaster, 10 mm, (2) reinforced concrete, 250 mm, (3) high-performance thermal insulation made of mineral fibres, 200 mm, λ = 0.04 W/(m.K), (4) ventilated air layer, 38 mm, and (5) aluminium sheet, 2 mm.

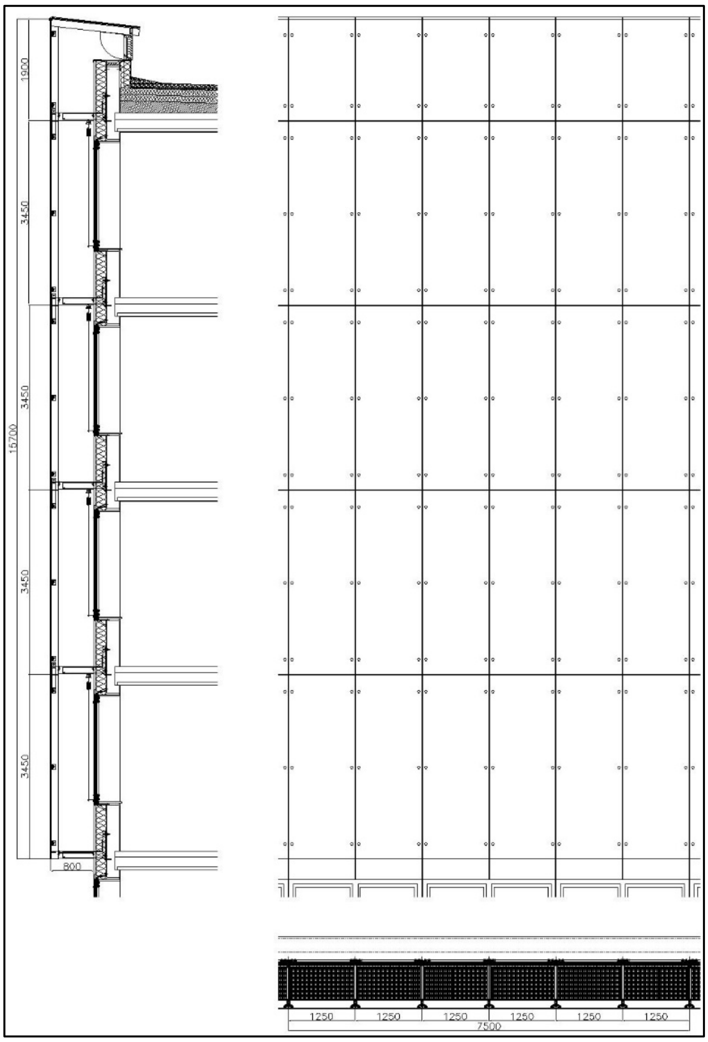

Figure 4. Structural design of the double-skin transparent facade.

The rooms are heated, with the room air temperature of +20.0 °C. Climatic conditions are represented by the design outdoor air temperature of -11.0 °C. There is an air intake opening at the bottom of the cavity. At the level of each floor, a floor grid with an effective area of 70 % is mounted along the entire facade. At the highest level of the cavity, in the centre, there is an air outlet opening with the dimensions 700 x 355 mm and the area of about 0.25 m^2. The investigated air flows rates through the facade are 50, 100, 150, and 200 m^3/min. As this is a stationary calculation, the intensity of solar radiation is statically modelled at four levels: 150, 300, 450, and 600 W/m^2 which, together with the above-defined airflows, form a matrix of 16 solutions. The double-skin facade was modelled in FLOVENT CFD simulation software (Fig. 6).

3.2. Climate data

The efficiency of utilization of the aerothermal energy significantly depends on the number of sunshine hours and the intensity of solar radiation. Fig. 5 and Table 1 show that in the region of Bratislava, Slovakia the duration of solar radiation above 600 W/m^2 is nearly 245 hours; it is 177 hours for the intensity in the range of 450 to 600 W/m^2, and 224 hours for the intensity in the range of 300 to 450 W/m^2 during heating season (October to April). The climate data is based on the test reference year.

Table 1. Intensity of solar radiation over a test reference year in Bratislava, Slovakia.

MESIACE	Intensity of the solar radiation (W/m2)													ALL
	0 - 50	50 - 100	100 - 150	150 - 200	200 - 250	250 - 300	300 - 350	350 - 400	400 - 450	450 - 500	500 - 550	550 - 600	nad 600	
January	615,2	17,7	13,0	10,1	7,8	9,3	10,0	9,3	14,2	10,3	6,7	7,3	13,3	**744,0**
February	515,2	22,9	11,6	9,7	7,2	7,8	9,6	11,3	9,5	8,5	12,9	10,7	35,3	**672,0**
March	537,3	38,3	11,0	13,6	9,5	9,8	9,3	8,3	7,7	8,4	10,1	10,5	70,3	**744,0**
April	443,9	29,7	23,8	23,3	18,3	17,3	23,8	21,4	10,3	10,3	10,9	14,1	72,9	**720,0**
May	412,4	38,4	18,9	15,8	10,8	10,4	13,8	22,3	23,2	17,8	20,7	14,9	124,6	**744,0**
June	396,8	25,8	28,3	24,3	15,3	14,9	15,3	9,6	9,0	14,1	24,8	22,6	119,3	**720,0**
July	389,3	39,4	31,8	24,6	22,6	20,2	21,3	22,5	18,0	20,1	18,1	21,3	94,9	**744,0**
August	413,7	31,0	42,9	20,8	16,8	14,5	19,8	28,6	16,6	17,2	20,1	16,9	85,2	**744,0**
September	474,7	24,5	22,3	28,6	17,8	15,7	23,9	21,4	10,8	9,4	13,5	8,1	49,5	**720,0**
October	542,2	23,2	28,1	18,3	11,1	10,4	9,3	13,1	13,7	11,0	9,8	8,5	45,5	**744,0**
November	614,9	31,4	16,3	11,1	7,4	6,6	5,8	6,1	6,8	6,7	2,3	0,9	3,8	**720,0**
December	646,7	20,6	8,7	8,2	6,7	8,2	7,8	8,2	8,4	5,3	6,1	6,0	3,3	**744,0**
YEAR	**6002,1**	**342,9**	**256,6**	**208,3**	**151,2**	**145,0**	**169,7**	**181,9**	**147,9**	**138,8**	**155,8**	**141,8**	**718,0**	**8760,0**
heat. season	**3915,3**	**183,7**	**112,4**	**94,2**	**67,9**	**69,3**	**75,6**	**77,6**	**70,4**	**60,3**	**58,8**	**58,0**	**244,5**	**5088,0**

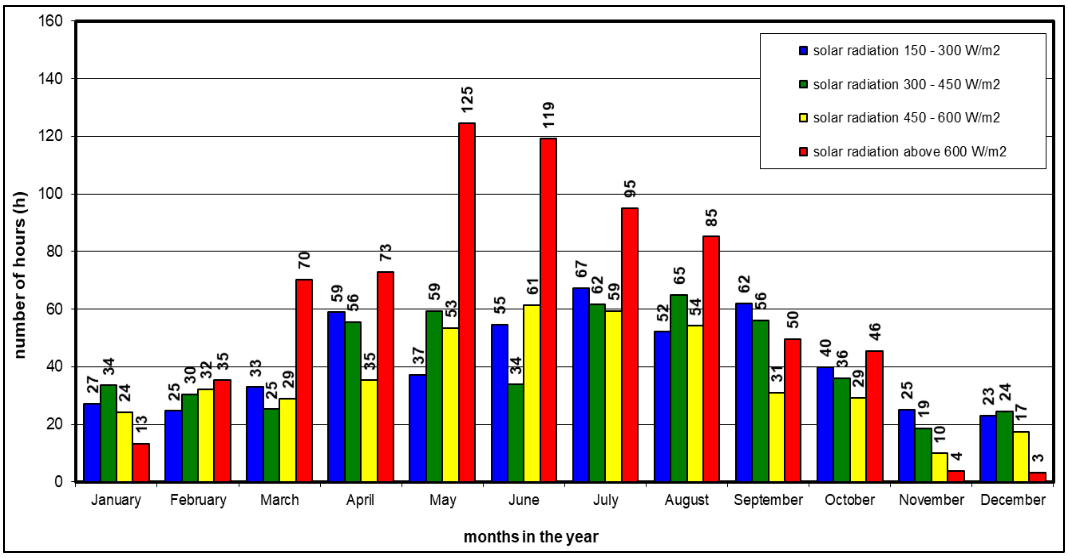

Figure 5. Intensity of solar radiation over a test reference year in Bratislava, Slovakia.

3.3. Results and discussion of the computer simulations

Fig. 6 shows a model of the facade in Flovent software together with an example of air velocity and air temperature profiles for the solar radiation of 600 W/m^2 and the primary air flow rate of the heat pump of 200 m^3/min. The outputs from Flovent software were utilized to calculate the rise of the air temperature in the double-skin facade (Fig. 7). All results refer to the design outdoor air temperature of -11 °C. Both the intensity of solar radiation and the air flow through the cavity considerably influence the air temperature at the outlet from the double-skin facade. The air temperature rise in the cavity reaches about 3.7 K for the minimum solar radiation of 150 W/m^2 and the maximum airflow of 200 m^3/min, up to almost 23.0 K for the maximum solar radiation of 600 W/m^2 and the minimum airflow of 50 m^3/min. Providing that the increase in air temperature at the inlet to the heat pump by 1 °C means an increase in its performance by about 2 %, utilization of thermally conditioned air from the double-skin transparent facade promises significant energy gains over the heating period.

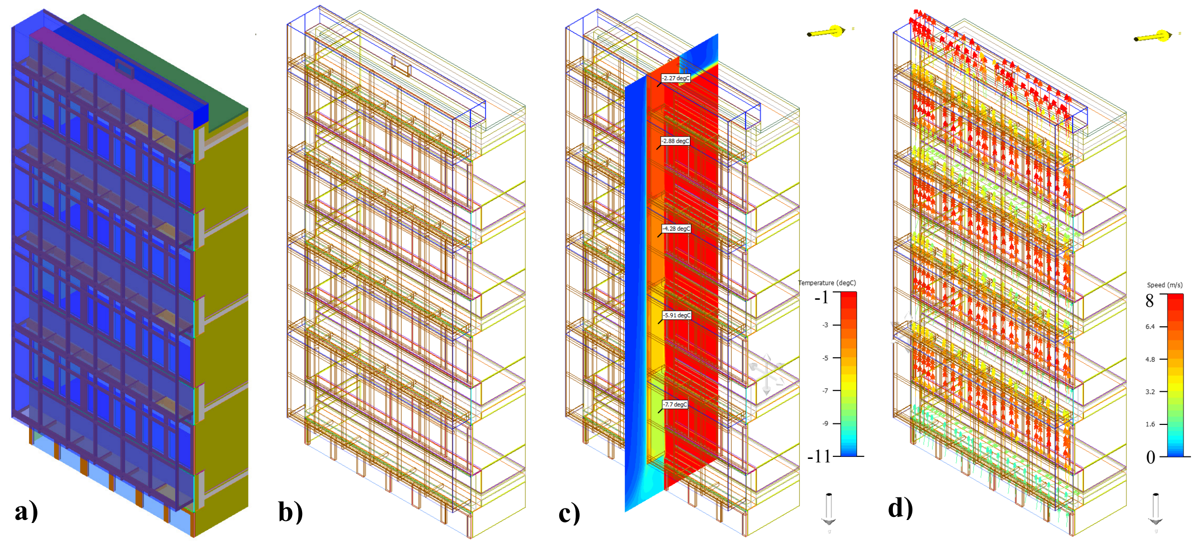

Figure 6. CFD model of double-skin facade in FLOVENT simulation software: a) geometry and materials b) transparent view, c) air temperature (°C), d) air velocity (m/s).

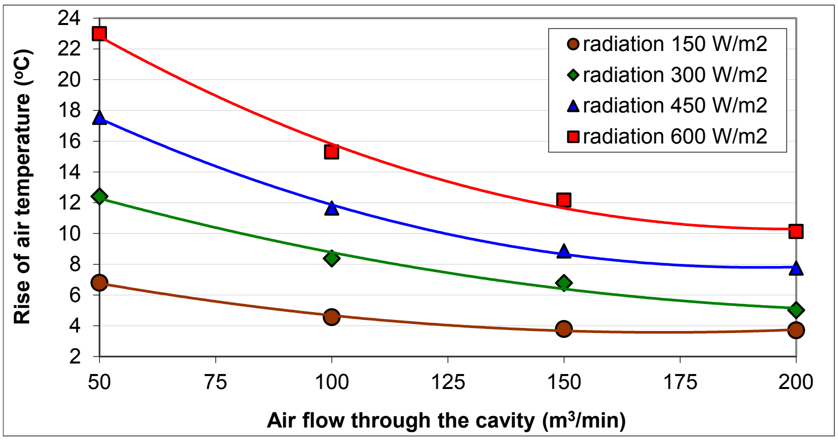

Figure 7. Rise of air temperature in the double-skin transparent facade as a function of intensity of solar radiation and air flow through the cavity.

3.4. The effect on the performance of air/water heat pump

An air/water heat pump Stiebel Eltron WPL 23 cool, suitable for collecting air from air channels and cavities, was used to demonstrate the effect of the double-skin facade on the performance of air/water heat pump. The air flow through the heat pump is estimated to be close to 100 m^3/min based on technical parameters of the heat pump. The relationship between air temperature at the inlet to the heat pump and COP is shown in Fig. 8 for the secondary temperature of the heat pump equal to 35 °C, 45 °C, 55 °C, and 60 °C. The calculation is based on the data regarding air temperature in the cavity as shown in Fig. 7 and the data regarding solar radiation presented in Table 1 and Fig. 5. The green arrows indicate the COP equal to 2.4 in the case when the primary air at the inlet to the heat pump is not preheated, i.e. fresh outside air is taken as the primary air. The red arrows refer to the situation when thermally conditioned air from the double-skin facade is used as the primary air for the heat pump. The calculations indicate that by thermally conditioning the primary air it is theoretically possible to increase the COP of the heat pump by 0.4.

To verify feasibility of the double-glazed transparent facade also for outdoor air temperatures lower than the design outdoor temperature of -11 °C, another set of simulations was performed for the outdoor air temperature of 0 °C. This outdoor air temperature represents temperate climate conditions in winter, typical for the region of Central Europe. For example, for the solar radiation of 600 W/m^2 and the air flow through the heat pump of 100 m^3/min there was almost no change in the difference between air temperature at the inlet to the facade and air temperature at the outlet from the facade. It was found, that the effect of solar radiation on the facade is crucial, whereas the effect of changing the outdoor air temperature from -11 °C to 0 °C is negligible. This means that all other conditions being the same, lower outdoor air temperature results in higher air temperature at the outlet from the double-glazed facade (inlet to the heat pump) and better COP of the heat pump.

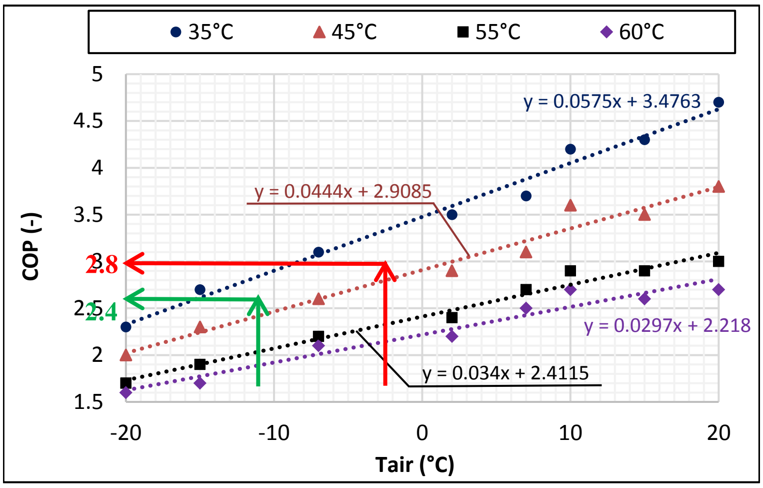

Figure 8. The relationship between air temperature at the inlet to the heat pump (T_{air}) and COP.

4. Conclusion

The facades of modern buildings should help optimize energy flows within the building through the use of optimized building structures and renewable energy sources. In this study we presented a concept of a two-stage system to utilize solar energy to preheat the primary air for an air heat pump. The computer simulations have shown that by thermal conditioning of the outside air in the cavity of a double-skin facade it is possible to substantially increase the temperature of the primary air for the heat pump. The difference between the temperature of fresh outside air and the temperature of thermally conditioned air at the outlet from the cavity was ranging from 4 K up to 23 K, depending on air flow through the primary side of the heat pump and solar radiation. Such increase in inlet temperature to the heat pump can significantly improve its COP.

Acknowledgments

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