

## Research Article

# Performance Modelling of Dual Air/Water Collector in Solar Water and Space Heating Application

Viacheslav Shemelin  and Tomas Matuska 

University Centre for Energy Efficient Buildings, Czech Technical University in Prague, Trinecka 1024,  
273 43 Bustehrad, Czech Republic

Correspondence should be addressed to Viacheslav Shemelin; [viacheslav.shemelin@cvut.cz](mailto:viacheslav.shemelin@cvut.cz)

Received 30 November 2018; Revised 24 January 2019; Accepted 6 February 2019; Published 18 April 2019

Guest Editor: Paolo Conti

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In the present work, the detailed mathematical model of a dual air/water solar collector (DAWC) has been developed and experimentally verified. To demonstrate the application of the DAWC, three buildings with different energy performance levels and three building locations were chosen in analyzed case studies. Four solar collector systems were compared with one another. The solar yield of the described systems was determined by simulation using the detailed theoretical model of DAWC. The results indicate that in the case of combining a domestic hot water preparation system and recirculating-air heating system based on DAWC, it is possible to achieve up to 30% higher solar energy yield compared to a conventional solar domestic hot water preparation system dependent on climate and building performance.

## 1. Introduction

Flat-plate solar collectors are probably the most fundamental and most studied technology for solar-power domestic hot water systems. Flat-plate collector technology has evolved over 60 years. Products on sale today have been proven to be durable and reliable, and therefore, collectors are considered as a fairly mature technology. However, even if this device has reached a good technological level and position in the market, the scientific and technological world has shown a constant attention to improve the energy performance of the collector. The ways of increasing the energy performance generally can be divided into two categories: the use of new technologies, materials, and components and the combination of already existing solar utilization technologies in one facility (hybrid collector).

The objective of combining two different solar utilization technologies is to make the application field for a given collector wider and increase the potential energy gain from the area occupied by the collector. A known example of such a multipurpose collector is a photovoltaic-thermal solar collector combining PV technology and a solar thermal collector.

The present study is focused on the dual-fluid solar collector, combining the air and liquid solar collectors. The idea of combining both types of technology in a dual air/water solar collector (DAWC) is not new. It has emerged from the typical situation in moderate and cold climatic zones, where solar radiation is sufficient for the preparation of hot water for households needs (50-60°C) during summer, whereas the output temperatures from solar collectors during winter generally do not reach values higher than 30°C; however, it can be sufficient, for example, for preheating fresh air. Such an integrated design allows increasing the annual energy yield of a solar system and maximizing the operating time, which makes it more cost-effective than the conventional solar water or air systems.

A number of researchers have studied the thermal performance of solar collectors working with two different types of fluids simultaneously. Assari et al. [1] presented a mathematical model for a dual air/water solar collector by the effectiveness method. The model was experimentally verified and subsequently used for the performance analysis of a dual air/water solar collector with three different kinds of air channels, such as rectangular fin, triangular fin, and without fin.

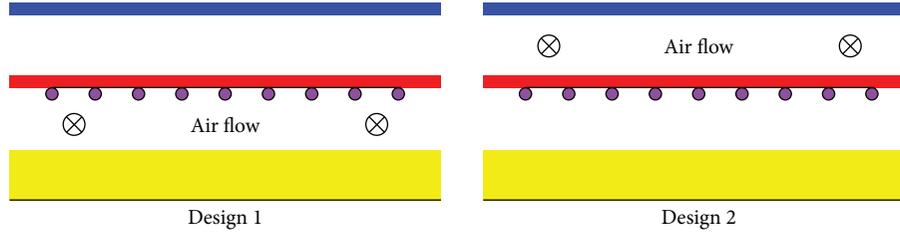


FIGURE 1: Solar DAWC designs considered in the Type 207 model.

The results of the modelling indicated that the rectangular fin has a better performance compared with the others. Jafari et al. [2] provided energy and exergy analysis of a dual air/water solar collector with triangle air channels. The study showed that the dual air/water solar collector has better energy and exergy efficiency than a conventional liquid or air collector. Ma et al. [3] presented experimental and theoretical analyses of the efficiency of a dual air/water solar collector with L-shaped fins and confirmed that the air flow rate is a key factor for thermal efficiency. Later, Mohajer et al. [4] conducted an experimental investigation of a dual air/water solar collector designed by Assari et al. [1]. The experiments showed that the system based on dual-purpose solar collectors could be used as a domestic drying system as well as for providing domestic hot water. Arun and Arun [5] concentrated their research on the utilization of a porous medium in the construction of a dual-purpose solar collector, and they indicated that the utilization of a porous medium leads to the increase in the thermal efficiency of the collector. Nematollahi et al. [6] presented an experimental comparison of a single-fluid solar system based on a liquid collector and a dual air/water solar system based on a dual air/water solar collector. The results showed that the dual air/water system has higher efficiency than a single-fluid system. Venkatesh and Christraj [7] provided an experimental investigation of a multipurpose solar collector system based on the combination of water and air collectors and confirmed its higher system efficiency compared with the conventional system. As opposed to the previous studies, Ji et al. [8] provided an analysis of the separate utilization of the air and water parts of a dual air/water solar collector. In the proposed system, a building-integrated dual-function solar collector will be used to provide space heating during a cold winter and water heating during summer. The results showed a decrease in heating load during winter and a reliably performing hot water preparation system during the summer season.

In the present study, the detailed theoretical model of DAWC has been developed and experimentally verified. Subsequently, the model had been used for annual performance simulation of four different solar systems. To demonstrate the application of the DAWC, three buildings from different locations and each with different energy consumptions were chosen as case studies. The distinctive feature of the presented study is a comparison of the different potential applications of dual air/water solar collectors for the buildings with different energy performance levels and different climatic conditions.

## 2. Detailed Theoretical Model of DAWC

To evaluate the energy performance of the different solar systems based on DAWC, the TRNSYS simulation environment was used. TRNSYS (transient system simulation program) is widely used for both solar and nonsolar simulation studies [9]. A system model consists of individual models of components, which are interconnected by linking the outputs of one component to the inputs of another. Each model is represented by parameters and inputs to compute outputs as a function of time. Since available TRNSYS libraries of component models do not contain any mathematical model of the DAWC collector, the detailed theoretical model of a dual air/water solar collector (Type 207) was created for use in the TRNSYS environment based on the previous models of a liquid solar collector (Type 205) and an air solar collector (Type 206). More detailed information about these models could be found in Shemelin and Matuska [10, 11] and Shemelin et al. [12].

The presented model does not imply the simultaneous work of the liquid and air parts. It means that DAWC model operates either as a liquid collector or as an air collector, depending on the Operating Mode. If the Operating Mode is equal to 0, the model operates as a liquid collector; if it is equal to 1, it operates as an air collector.

**2.1. Description of the Model.** The presented model is a detailed mathematical model developed for thermal performance simulations of two different solar collector designs. The considered designs of DAWC are shown in Figure 1. Design 1 represents an absorber pipe upper-bond configuration with a single air flow between the absorber and the bottom frame insulation. Design 2 represents an absorber pipe upper-bond configuration with a single air flow between the absorber and transparent cover.

The DAWC can be specified by a variety of detailed parameters, such as the optical properties of the transparent cover and absorber and the thermophysical properties of the main components of the solar collector. Moreover, the transparent cover (a single-glazing, transparent-insulation structure) and the back thermal insulation are defined by temperature-dependent thermal conductance.

The presented model of DAWC solves the one-dimensional energy balance of the solar collector under steady-state conditions according to the principle of the Hottel-Whillier equation for usable thermal output:

$$\dot{Q}_u = A_{\text{abs}} F_R [(\tau\alpha)_n G_t - U(T_{\text{in}} - T_{\text{amb}})]. \quad (1)$$

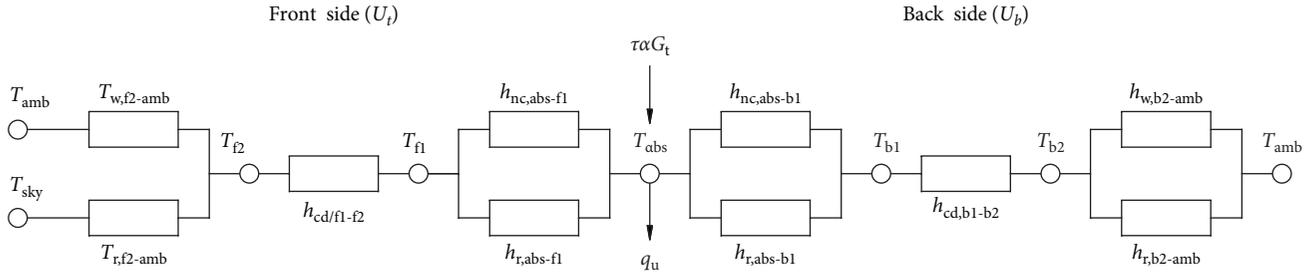


FIGURE 2: The thermal network of external energy balance if Operating Mode is equal to 0—a liquid collector.

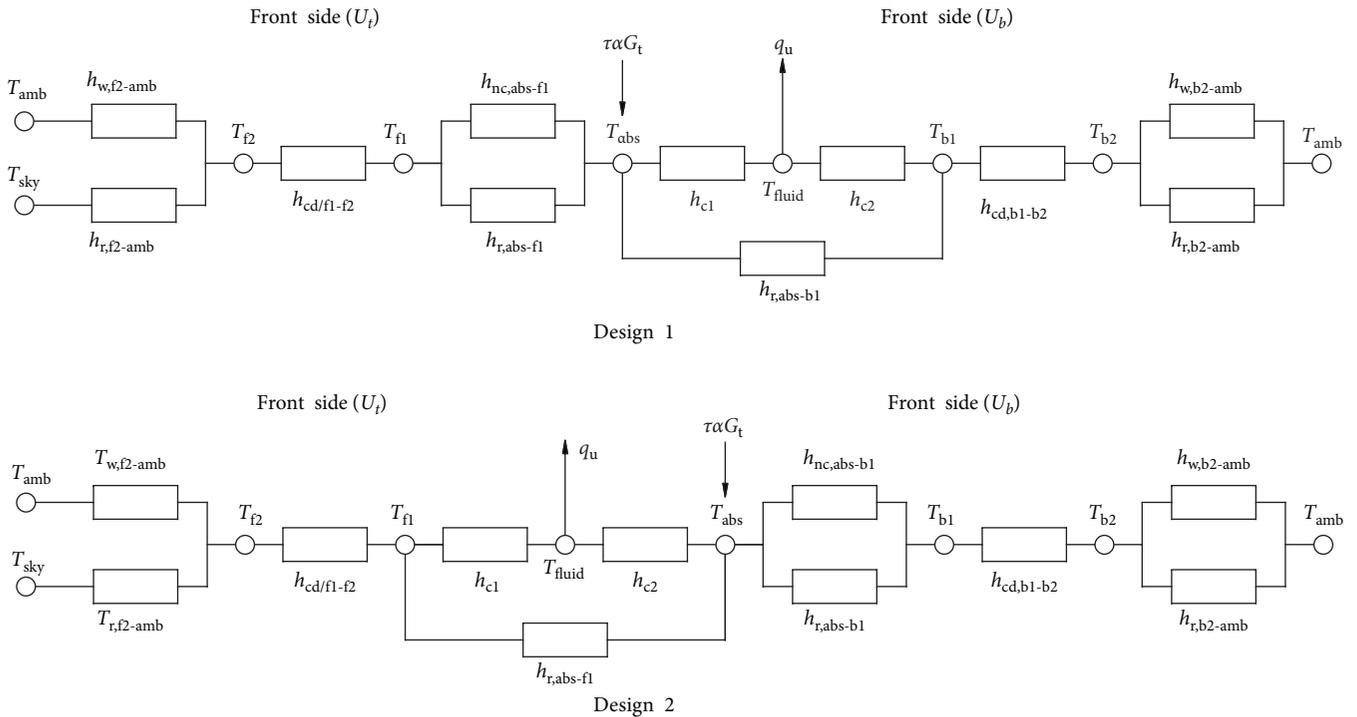


FIGURE 3: The thermal network of external energy balance if Operating Mode is equal to 0—a liquid collector.

In this equation,  $A_{abs}$  is the absorber area ( $m^2$ ),  $F_R$  is the collector heat removal factor (-),  $\tau$  is the solar transmittance of the collector cover (-),  $\alpha$  is the solar absorptance of the absorber (-),  $G_t$  is the total solar irradiance ( $W/m^2$ ),  $U$  is the overall heat loss coefficient of the collector ( $W/m^2 \cdot K$ ),  $\vartheta_{in}$  is the inlet fluid temperature (K), and  $T_{amb}$  is the ambient temperature (K).

The proposed model in general consists of two parts solved in iteration loops: the external energy balance of the absorber (heat transfer from the absorber surface to the ambient environment, see Figures 2 and 3) and the internal energy balance of the absorber (heat transfer from the absorber surface into the heat transfer fluid). Both the external and internal energy balances are mutually dependent. The overall collector heat loss coefficient  $U$  (temperature dependent) as the main output from the external balance is one of the inputs for the internal balance. On the other side, the mean absorber temperature  $T_{abs}$  (K) as the output from

the internal balance is used as the input for the external balance. Since heat transfer coefficients are temperature dependent, the surface temperatures for the main planes of a collector are calculated in the iteration loop until consecutive results of the mean temperatures differ by less than 0.01 K.

Another iteration loop has been introduced to transfer the results from the external balance to the internal balance and the results from the internal balance to the external balance. The basic electric analogy of the proposed model is presented in Figures 2 and 3. A more detailed description of the proposed model could be found in Shemelin et al. [12].

The model was implemented in a TRNSYS environment, as Type 207 offers the parametric analysis for different construction alternatives for annual solar collector performance in the given solar system application. There is also a possibility to change mathematical correlations describing the fundamental heat transfer phenomena (natural convection,

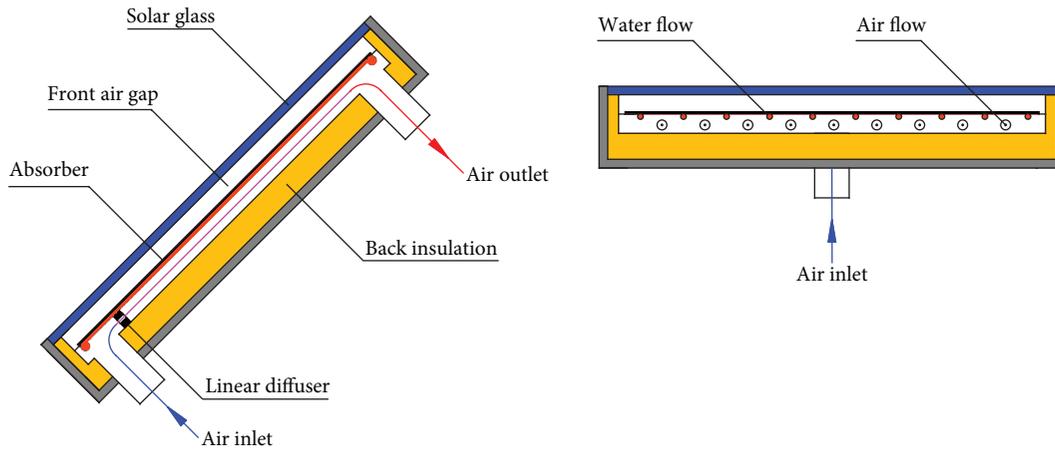


FIGURE 4: Design of the prototype of DAWC.



FIGURE 5: The experimental testing of the liquid and air parts of DAWC.

wind convection, forced convection, etc.) and to perform sensitivity analysis for selected correlations.

**2.2. Model Verification.** The model has been experimentally verified on a prototype of DAWC (see Figure 4) in the frame of solar collector testing according to the European standard EN ISO 9806 within the accredited Solar Laboratory of the Czech Technical University in Prague. The testing of the liquid and air parts has been conducted separately (see Figure 5). The prototype of DAWC has been built from the experimental solar water collector by adjusting the interior air gap. The detailed parameters of the produced prototype are listed in Table 1. If the Operating Mode is liquid heating, water flows in the copper tubes and the air channels are closed at the inlet and outlet. On the

other hand, the inlet and outlet of water pipes are closed in the air heating mode.

Figures 6 and 7 show experimentally evaluated efficiency points and theoretically modelled efficiency characteristics both in the liquid and air operating modes. Experimental data points of solar collector efficiency are coupled with combined standard uncertainty bars in the graphs. The uncertainty analysis has been provided based on methodology published in Mathioulakis et al. [13] and Müller-Schöll and Frei [14]. The theoretical calculation of the efficiency characteristic by the model is subjected to the uncertainty of real collector parameters which are used as inputs for the model. Therefore, the results of the theoretical calculation could be presented as two delimiting curves where the collector efficiency values can be found in reality. It is evident from the

TABLE 1: Main parameters of the dual air/water solar collector.

Collector parameter	Value	Collector parameter	Value
Dimensions (W/L/H)	$1 \times 1.6 \times 0.087$ m	Absorber emissivity	0.05
Area (gross, aperture, absorber)	$1.6 \text{ m}^2, 1.52 \text{ m}^2, 1.49 \text{ m}^2$	Header pipe	Cu $22 \times 1$ mm
Cover material	Solar glass 4 mm	Number of riser tubes	10
Front air gap thickness	30 mm	Distance between riser pipes	100 mm
Absorber material	Aluminium 0.4 mm	Air flow channel	10 mm
Cover transmittance	0.92	Back insulation thickness	40mm
Absorber absorptance	0.95	Insulation material	Rockwool

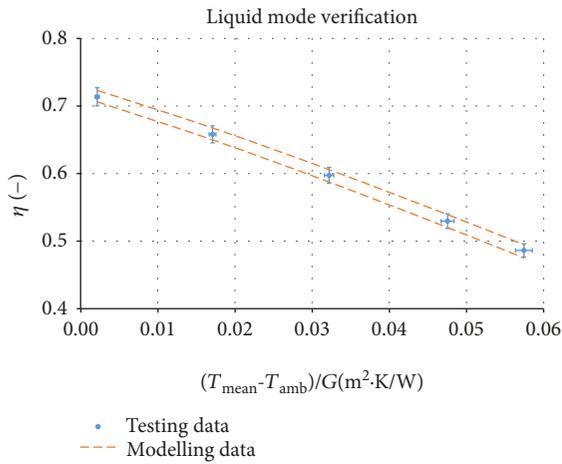


FIGURE 6: Mathematical model verification—liquid heating mode.

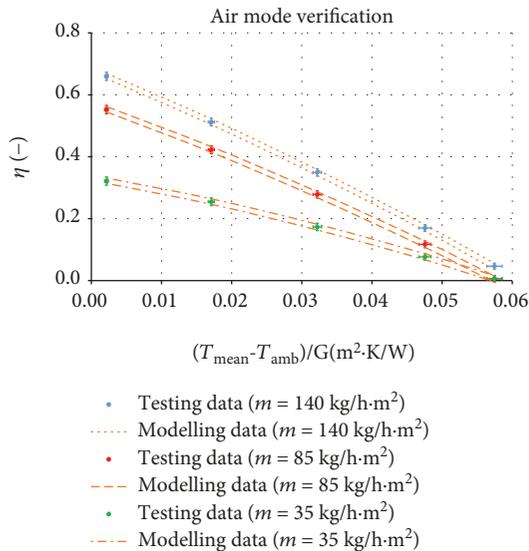


FIGURE 7: Mathematical model verification—air heating mode.

results that simulated efficiency characteristics fit the measurements relatively well, which gives confidence in the developed model. More information about model verification and uncertainty analysis can be found in Shemelin et al. [12].

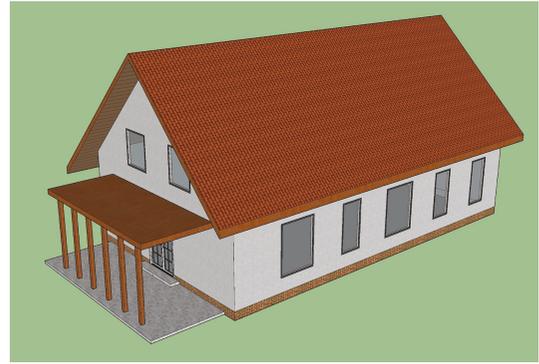


FIGURE 8: Three-dimensional geometry of the considered buildings.

### 3. Case Studies

To evaluate the energy performance of the DAWC solar system, the system's annual solar yield has been analyzed for a specific site and under specific conditions. Three single-family houses (buildings A, B, and C) (see Figure 8) from different locations (Stockholm, Prague, and Milan) and each with different energy performance levels were considered as case studies for comparative analysis. The detailed building parameters are listed in Table 2. To provide calculations of the total heat demand, the simulation software TRNSYS 17 was used. The climate data used in the analysis were taken from TMY (Meteonorm) for Stockholm, Prague, and Milan. The climatic conditions of the considered sites are listed in Table 3. The results of the modelling are outlined in Figures 9 and 10.

### 4. Solar Systems

To provide comparative analysis of the potential applications of the dual air/water collectors, four different solar energy systems were analyzed. The reference system (RS) is a conventional solar domestic hot water system (see Figure 11) designed with conventional flat-plate liquid collectors with the following parameters: optical efficiency, 0.81; linear heat loss coefficient,  $3.58 \text{ W/m}^2\cdot\text{K}$ ; quadratic heat loss coefficient,  $0.0045 \text{ W/m}^2\cdot\text{K}^2$ ; and incidence angle modifier,  $\text{IAM}_{50} = 0.92$ . The detailed parameters of the reference system are listed in Table 4. There is a different collector area design

TABLE 2: Main parameters of buildings in the analysis.

Key values	Building A	Building B	Building C
		General data	
Occupancy		4 persons	
Climate data source		TMY, Meteororm	
Set point temperature (day/night)		20°C/20°C	
Ventilation air flow rate		100 m <sup>3</sup> /h	
Efficiency of heat recovery unit		75%	
Internal gains (occupants + equipment)		2 W/m <sup>2</sup>	
Weighted mean <i>U</i> value	0.187 W/m <sup>2</sup> ·K	0.375 W/m <sup>2</sup> ·K	0.489 W/m <sup>2</sup> ·K
		Building geometry data	
Gross floor area		286 m <sup>2</sup>	
Heated floor area		246 m <sup>2</sup>	
Ventilated volume		607 m <sup>3</sup>	
		Hot water consumption	
Cold water temperature		Based on TMY	
Hot water temperature		55°C	
Tap profile		160 l/day (7.00: 65 l; 12.00: 30 l; 19.00: 65 l)	

TABLE 3: Climatic conditions of considered sites.

Annual values	Stockholm/Sweden	Prague/Czech Republic	Milan/Italy
Latitude	59.65°N	50.10°N	45.43°N
Mean ambient temperature	5.3°C	7.9°C	11.7°C
Minimum ambient temperature	-19.9°C	-15.2°C	-7.7°C
Maximum ambient temperature	28.3°C	30.7°C	45.1°C
Global solar horizontal irradiation	981 kWh/m <sup>2</sup>	999 kWh/m <sup>2</sup>	1255 kWh/m <sup>2</sup>
Global solar irradiation on tilted surface (South, 45°)	1231 kWh/m <sup>2</sup>	1114 kWh/m <sup>2</sup>	1392 kWh/m <sup>2</sup>

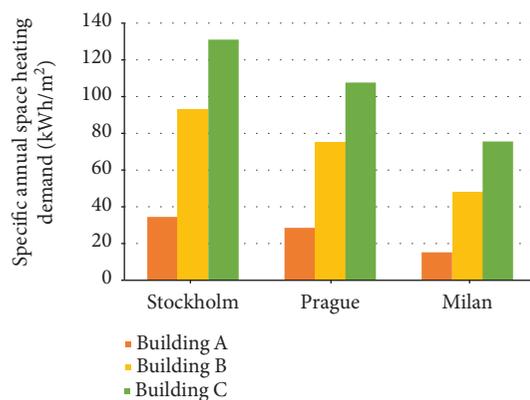


FIGURE 9: Specific space heating demand for buildings and locations.

for each different location to achieve a similar solar fraction for the hot water heating application ( $60 \pm 7\%$ ).

The first alternative system (V1) is based on a DAWC which operates during the hot season in a liquid mode for hot water preparation and then operates for the rest of the

year (cold season) for the preheating of fresh air before it enters the heat recovery ventilation unit (see Figure 12). In the air heating mode, the fresh air is led through the collector and then optionally heated in the heat recovery ventilation unit. In the case of insufficient sunlight (cloudy sky or night time), the air bypasses the collector.

The second system (V2) has the same configuration as the first alternative (V1) with the exception that the collector is installed at the output of the heat recovery ventilation unit. In the air heating mode, the fresh air is firstly preheated in the heat recovery ventilation unit and then optionally is led through the collector (see Figure 13). The preheated air is led through the collector only in cases when the collector has a potential to heat up the air, otherwise the preheated air bypasses the collector.

The third system (V3) differs from the previous two systems—the DAWC operates during the hot season in a liquid mode for hot water preparation and then operates for the rest of the year (cold season) as a solar air collector for a direct recirculating air heating system (see Figure 14). In the air heating mode, the circulating air from the rooms is heated in the collector and then it is led back to the building. The fresh air, after preheating in the heat recovery unit, is mixed

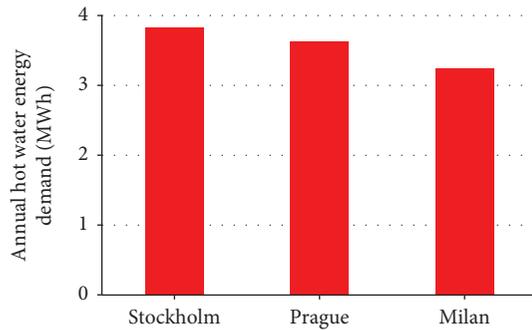


FIGURE 10: Hot water heating demand for given locations.

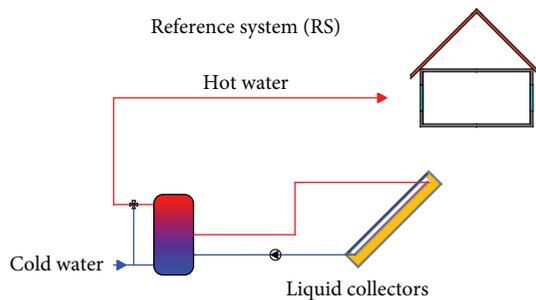


FIGURE 11: The configuration of the reference system (RS).

with the circulation air and only after is it brought into the living rooms. On cloudy days and at night, the circulation air does not flow through the collector. The main feature of this variant is that the flow rate is not limited by the ventilation air flow rate and could be increased up to  $400 \text{ m}^3/\text{h}$ .

The duration of the hot and the cold seasons is different for each system and is dependent on the climatic conditions and the total heat demand of the building. Basically, the mathematical model of DAWC is able to determine in which mode (water or air heating mode) it should operate to get the maximum performance.

The design parameters of the DAWC collector which were used in the simulation of all alternative systems (V1, V2, and V3) are the same as the prototype DAWC and are listed in Table 1. The solar domestic hot water system parameters in the liquid mode are the same as for the reference system and are listed in Table 4. The air heating mode system parameters and operating conditions are shown in Table 5.

## 5. Results and Discussion

To demonstrate the application of the DAWC, three buildings (buildings A, B, and C) from three different locations (Stockholm, Prague, and Milan) and each with different energy performance levels were chosen as case studies for comprehensive analysis. Four different solar systems were compared in the analysis. The solar yield of the described systems was determined by detailed simulations in TRNSYS as the difference in the total heat demand of a building with and without a solar system. The results of the simulation

are shown in Table 6. Values in parentheses indicate the relative difference between the given alternative and the reference system.

Firstly, the results of the simulation indicate that the DAWC design allows increasing the annual energy yield of the solar system depending on the building type and climate. It can be explained by the fact that during the cold season the intensity of solar radiation is not sufficient to heat the liquid in the collector to a usable temperature for domestic hot water supply, but on the other hand, it is sufficient to heat the ambient fresh air at low temperature or the circulation air at the temperature of the room. Besides, it can be seen that the higher building heat energy consumption is correlated to the higher solar energy yield of the compared systems. It means that the DAWC in an air heating mode not only reduces the ventilation heat loss but also contributes to a reduction of the space heating demand.

Secondly, it can be observed that the alternative system V3 shows the highest annual solar energy yield among the compared systems. This result is a consequence of the higher efficiency of DAWC (air heating mode) due to the favorable operating conditions. The efficiency of the air part of DAWC depends on a number of parameters, but the collector air flow rate is dominant (see Figure 5). In the case of the alternatives V1 and V2, the collector air flow rate is limited by the ventilation air flow rate of  $100 \text{ m}^3/\text{h}$ , while in the case of the alternative V3, the air flow is increased to  $400 \text{ m}^3/\text{h}$ .

In the case of the alternative V1, the performance of the heat recovery unit is limited because the air temperature after DAWC could be significantly higher than the outdoor temperature. Moreover, if the fresh air temperature after DAWC is higher than  $18^\circ\text{C}$ , the fresh air bypasses the heat recovery unit and flows directly to the building. Here, the solar DAWC replaces the heat recovery for the ventilation.

If the collector is placed behind the heat recovery unit to provide an additional rise in temperature to the room inlet air, the collector system is energetically more favorable (system V2). Nevertheless, the efficiency of DAWC is limited because the air temperature after the heat recovery unit is higher than the outdoor temperature and consequently the solar collector thermal losses are higher compared to the configuration in system V1.

Naturally, the combination of the DAWC system with heat recovery from the exhaust air reduces the possible heat savings by the DAWC collector. Here, the DAWC and heat recovery system are competing systems and the potential savings are thus limited in total.

Finally, the simulation results show that the DAWC solar system is more efficient in cold and moderate climatic zones than in warm climatic zones. For warm climates, the ambient air temperature during the day in winter is high and space heating demand is low, so the performance of the DAWC (air heating mode) is limited. On the other hand, there is still high hot water energy demand which is not practically limited during winter. As a result, sometimes it is more efficient for DAWC to operate in liquid mode during winter than in the air heating mode for warm climates. Similarly, the larger potential for the DAWC application is indicated for buildings with a higher space heating demand.

TABLE 4: Solar domestic hot water system parameters and operating conditions for given alternatives (RS, V1, V2, and V3).

Parameter	Description
Collector orientation	South, 45° (based in the roof slope)
Collector area	Stockholm and Prague: 4.8 m <sup>2</sup> ; Milan: 3.2 m <sup>2</sup>
Collector mass flow rate	50 l/h·m <sup>2</sup>
Heat transfer medium	Propylene glycol
Pump control	Pump switching on/off temperature difference collector-storage 8 K/2 K
Piping	Supply and return pipes are located in the internal and external environments: 10 m each, DN 16 with 25 mm thermal insulation ( $\lambda = 0.04 \text{ W/m}^2 \cdot \text{K}$ )
Heat exchanger	Smooth tube heat exchanger with $UA = 400 \text{ W/K}$ ( $\pm 15\%$ ) for 42°C/40°C (inlet temperature/tank storage temperature)
Tank storage	Volume: 200 l; heat loss: 1.4 kWh/day; height/diameter ratio: 2.5

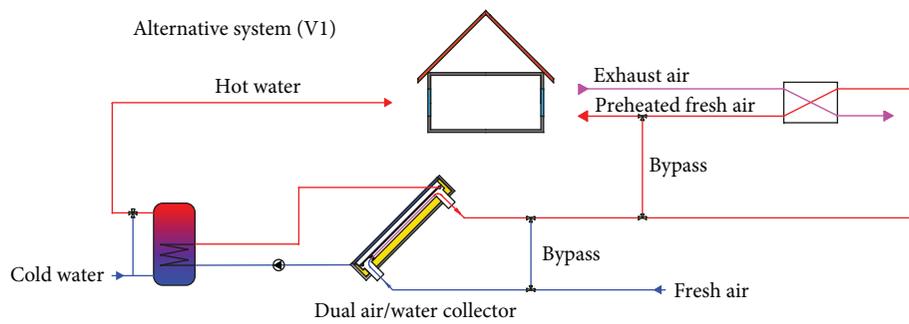


FIGURE 12: The configuration of the alternative system V1.

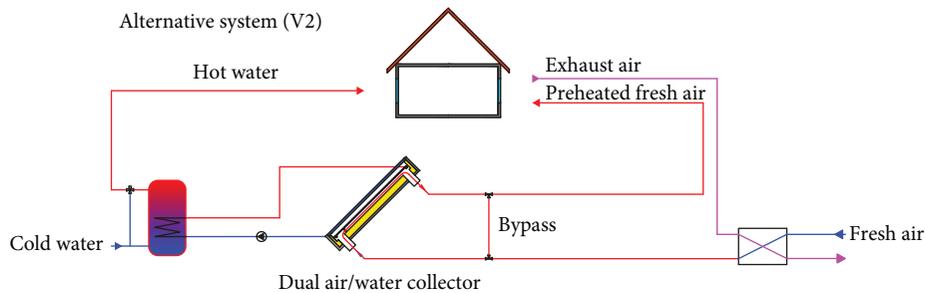


FIGURE 13: The configuration of the alternative system V2.

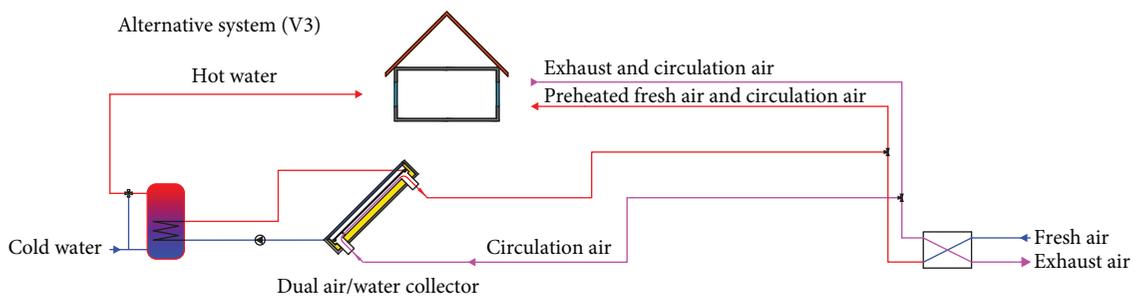


FIGURE 14: The configuration of the alternative system V3.

TABLE 5: Air heating mode (V1, V2, and V3).

Parameter	V1	V2	V3
Collector orientation	South, 45° (based on the roof slope)		
Collector area	Based on the collector area for the reference variant		
Set point temperature	22°C		
Function	Fresh air preheating (before HR unit)	Fresh air preheating (after HR unit)	Direct air heating (recirculating air)
Air flow rate	100 m <sup>3</sup> /h	100 m <sup>3</sup> /h	400 m <sup>3</sup> /h

TABLE 6: The simulation results of the annual solar energy yield of the compared systems.

	RS (kWh/m <sup>2</sup> )	V1 (kWh/m <sup>2</sup> )	V2 (kWh/m <sup>2</sup> )	V3 (kWh/m <sup>2</sup> )
Stockholm				
Building A	418	418 (0%)	439 (5%)	460 (9%)
Building B	418	424 (1%)	461 (10%)	494 (16%)
Building C	418	456 (9%)	511 (20%)	582 (32%)
Prague				
Building A	426	426 (0%)	432 (1%)	448 (5%)
Building B	426	427 (0%)	443 (4%)	474 (11%)
Building C	426	437 (2%)	467 (9%)	529 (22%)
Milan				
Building A	677	677 (0%)	677 (0%)	680 (0%)
Building B	677	677 (0%)	684 (1%)	692 (2%)
Building C	677	681 (1%)	711 (5%)	739 (9%)

## 6. Conclusions

A detailed mathematical model of DAWC has been developed and verified by the experimental testing of the collector in liquid and air heating modes. Subsequently, the comprehensive analysis of different solar systems based on DAWC for three building types (energy performance levels) in three climatic locations has been provided.

Based on the simulation using practical design data, the following can be concluded:

- (i) The alternative V3 with the application of DAWC in the air recirculation heating system shows the highest annual solar energy yield among the compared systems. Depending on the building type, the proposed system V3 allows increasing the annual energy yield of the solar system by up to 32% for the Stockholm climatic conditions, by up to 22% for the Prague climatic conditions, and by up to 9% for the Milan climatic conditions as well
- (ii) The DAWC system is more efficient for buildings with high heat energy consumption, located especially in moderate and cold climates. For instance, for moderate climatic conditions and for a building with “high” heat energy consumption the annual energy yield of the alternative solar system V3 is about 103 kWh/m<sup>2</sup> higher compared to the

reference system RS. On the other hand, for the same climatic conditions and for a building with “low” heat energy consumption the annual energy yield is only 22 kWh/m<sup>2</sup> higher compared to the reference system RS

- (iii) The combination of the DAWC system with heat recovery from the exhaust air reduces the potential heat savings

## Data Availability

The detailed simulation results are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

## Acknowledgments

This work has been supported by the Ministry of Education, Youth, and Sports within the National Sustainability Programme I, project No. LO1605.

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