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Approximate and CFD energy performance analyses of industrial heating by water strip modules Part 2

Analisi approssimata e CFD delle prestazioni energetiche di sistemi di riscaldamento industriale con termostrisce radianti Parte 2

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Abstract

The objective of this study is the theoretical evaluation of the energy performance and comfort conditions of an industrial environment heated by a radiant strip heating system fed with hot water, which operates in steady state conditions, by varying the operating conditions. The analysis is carried out in two successive steps: firstly, the convective coefficients and the heating power (both convective and radiant part) of the heating system are evaluated by simulating heat exchange conditions similar to real operations, in comparison with the nominal data according to EN14037 standard. To carry out this preliminary assessment, different references in the scientific literature are considered concerning experimental measurements and/or numerical simulations of similar applications (low or medium temperature radiant heating systems in large rooms). In the second step of this study (the second part of this article), the analysis is deepened by CFD simulations to confirm the preliminary assessments..

Keywords:

- Radiant system
- Water strips
- Industrial heating
- Energy efficiency
- CFD

Sommario

L'obiettivo dello studio è la valutazione teorica delle prestazioni energetiche e delle condizioni di comfort all'interno di un ambiente industriale prodotte da un sistema di riscaldamento a strisce radianti alimentate ad acqua calda che opera in condizioni di regime stazionario al variare delle condizioni al contorno. L'analisi viene svolta in due fasi successive: in una prima fase, vengono quantificati i coefficienti convettivi e le rese (quota convettiva e radiante) del sistema di riscaldamento simulando situazioni di scambio termico vicine alla realtà, a confronto con i dati nominali secondo norma EN14037. Per svolgere questa valutazione preliminare ci si è basati su fonti reperite in letteratura scientifica inerenti misure sperimentali e/o simulazioni numeriche di applicazioni simili (sistemi di riscaldamento di tipo radiante a bassa o media temperatura in ambienti di grandi dimensioni e/o volumetrie). In una seconda fase dello studio, oggetto della seconda parte di questo articolo, l'analisi viene approfondita mediante simulazioni CFD al fine di confermare le valutazioni preliminari.

Parole chiave:

- Sistema radiante;
- Termostrisce radianti;
- Riscaldamento industriale;
- Efficienza energetica;
- CFD

Introduction

As already mentioned in the first part of this study, the advantage of using the technology of water strips lies in the extensive exploitation of heat transmission through radiation and convection. Usually, the former accounts for the greatest part of the heat transferred by the plate to the environment, but the latter can play an important role because of the non-negligible contribution of the natural convection.

Moreover, in an industrial building, a constant movement of air can be expected, for example, by means of a ventilation system. More generally, the presence of doors, windows or skylights, and indoor air evacuation towers can induce air flow, especially during winter when the temperature difference between the inside and outside of the shed is relevant. Therefore, it is interesting to analyze the behavior of the water strip heating system when there is no air movement compared with a condition where an air flow is expected.

In this part of the study, a numerical analysis by Computational Fluid Dynamics (CFD) is reported to investigate the thermal performance of the water strips in the two operating conditions just described. Due to reasons of computational effort, the analysis is conducted using a two-dimensional model of an industrial shed. The effectiveness of the use of the water strip heating system is demonstrated, above all in the operating conditions with air flow (a more frequent situation in an industrial context).

METHODS

In this section, the thermo-fluid dynamics analysis for the water strip heating system of an industrial shed is reported. In particular, for both the conditions investigated, the geometric model, the generated calculation grid, and the boundary conditions are reported. In the next section, the results are presented and discussed.

Numerical analysis

As the study is under transient conditions ("unsteady"), a sensitivity analysis was preliminarily conducted to identify the optimal time step to be set. Since the operating conditions feature convective air flow due to density gradients (temperature) and radiative heat exchange, it was necessary to set the time step in the order of a hundredth of a second. Five values were tested: 0.1, 0.05, 0.025, 0.01, 0.005 s. With time steps of 0.1 and 0.05 s, the solution diverged. Therefore, the value of 0.01 s was finally fixed as the best trade-off between computational effort and accuracy of the solution. The "unsteady" simulation lasted when the curve of the specific power (W m^{-1}) exchanged by the plates as a function of time reached an asymptotic value (see next section).

The radiation was considered by implementing the "Surface-To-Surface, S2S-radiation" model [17]. Two cases were simulated: for case 1 (negligible air flow, natural convection), the flow of air was simulated by setting the "laminar" model. For case 2 (constant air flow, forced convection), the activation of the *k-ε* turbulence model was considered [18].

Case 1: Radiation and natural convection

As shown in Figure 1, a two-dimensional section of an industrial shed was modeled. The reference is that of the first part of the paper. The shed was approximated with a double trapezoid, each with a smaller base, greater base, and height of 8.0, 9.5, and 6 m, respectively. The water strips, 0.9 m wide and 0.1 m high, are positioned with a 3 m pitch as shown in Figure 1a. As a consequence, a 12 m wide shed has 3 plates.

The mesh obtained by the geometric model features cells in a square or rectangular shape, with a maximum size of 0.05 m. Near the water strip plates, the calculation grid was thickened by means of a refinement procedure. The mesh sensitivity analysis demonstrated that the optimal mesh configuration shows the best compromise between solution accuracy and computational effort, and it is constituted of about 22000 elements (Figure 1b).

Figure 1c shows the boundary conditions applied to the external edges of the geometric model in terms of global transmittance of the walls (U_g). They already take into account the conductive resistance through the walls and the convective one on the external side. By defining T_{wall}

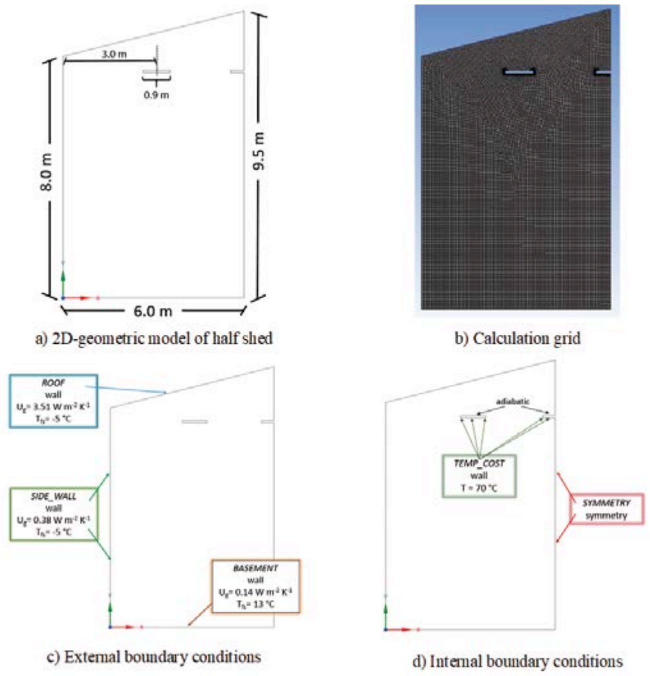

Figure 1 – The model of the shed building for case 1

Figura 1 – Modello del capannone per il caso 1

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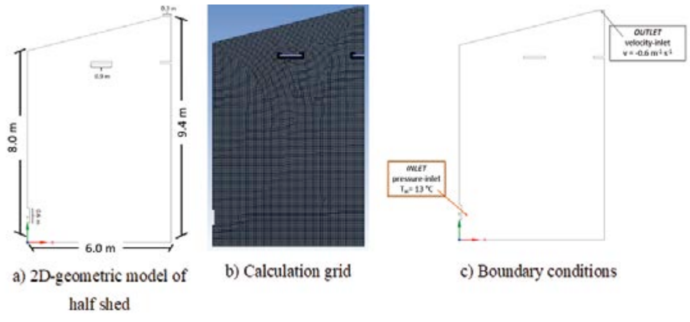

Figure 2 – The model of the shed building for case 2

Figura 2 – Modello del capannone per il caso 2

the internal temperature of each edge, L its length, T_{fs} the temperature of the external fluid, the software takes into account the specific average power per linear meter q_w [W m^{-1}] for each side, using the following equation:

$$|q_w| = |U_g L (T_{wall} - T_{fs})|$$

To keep the outline of any symmetries, it is necessary to identify the axis of symmetry and assign the suitable condition (Figure 1d).

Three sides of the strip (lower base and the two heights) were kept at a constant temperature of 70 °C (average operating temperature). Differently, the adiabatic condition was assigned to the upper side, thus simulating a thermal insulated water strip.

Case 2: Radiation and forced convection

Figure 2a shows the geometry used for the system's performance analysis in the case of a constant air flow inside the building. There is an opening of 0.6 m height at the bottom left, from which external air enters the shed. At the top right, an opening of 0.3 m width (i.e., half of the radius of a 0.6 m diameter suction tower placed on the roof) is set. Forced convection is simulated by imposing a constant mass flow (or air speed) at the outlet ("Outlet" in Figure 2c).

As regards the generation of the mesh, the same considerations and hypotheses previously described can be considered. In addition to the boundary conditions already shown in Figure 1, the insertion of a pressure inlet (for the "Inlet" section) and a negative velocity inlet (for the "Outlet" section) is considered (Figure 2c). The renewal air temperature is set at 13 °C, thus taking into account the enthalpy contribution of any heat recovery unit (a typical situation in industrial environments).

RESULTS AND DISCUSSION

Firstly, the results of case 1 are reported. As shown in Figure 3, the simulation was stopped when the curve interpolating the values of the

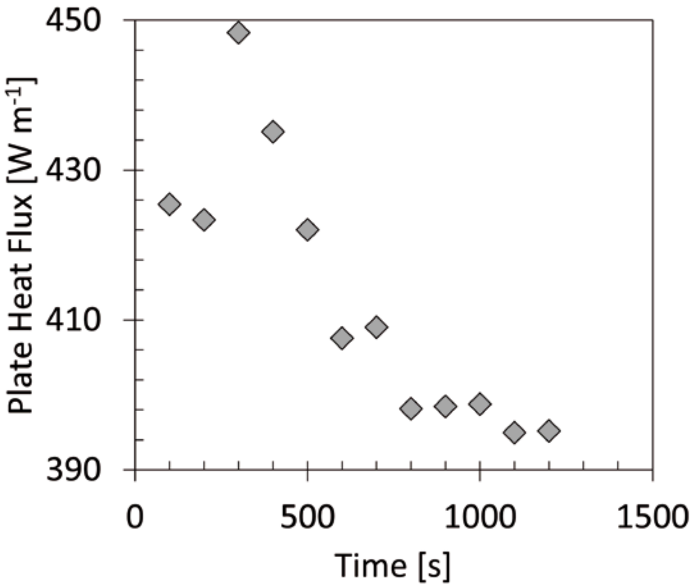

Figure 3 – Case 1, specific thermal power exchanged by the water strip

Figura 3 – Caso 1, potenza termica specifica scambiata dalla termostriscia

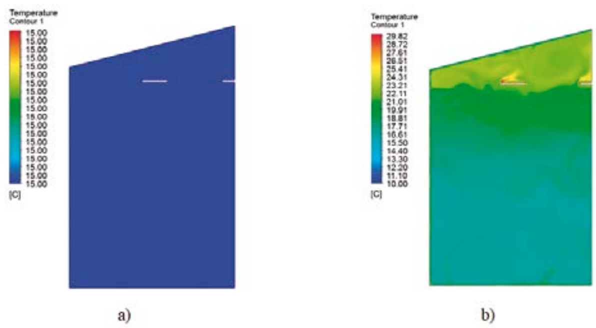

Figure 4 – Case 1, contour indoor air temperature: a) 0 s; b) 1000 s

Figura 4 – Profilo di temperatura dell'aria interna: a) 0 s; b) 1000 s

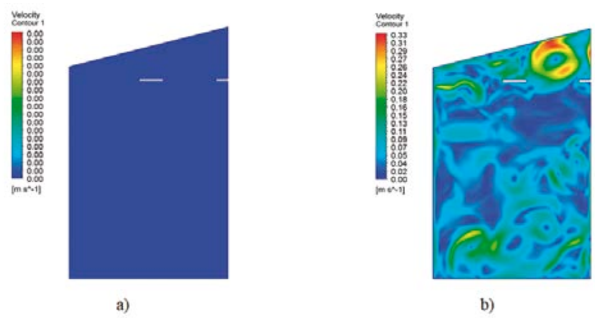

Figure 5 – Case 1, contour indoor air velocity: a) 0 s; b) 1000 s

Figura 5 – Profilo di velocità dell'aria interna: a) 0 s; b) 1000 s

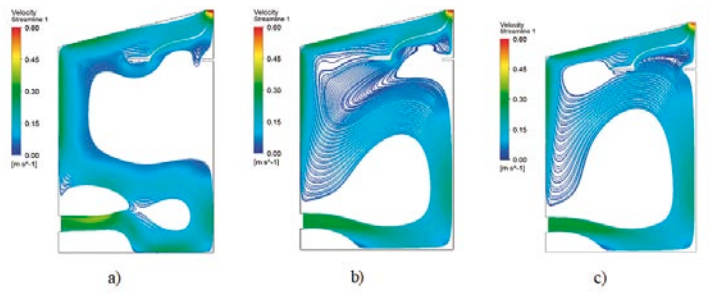

Figure 6 – Case 2, flow lines: a) 100 s; b) 400 s; c) 700 s

Figura 6 – Caso 2, linee di flusso: a) 100 s; b) 400 s; c) 700 s

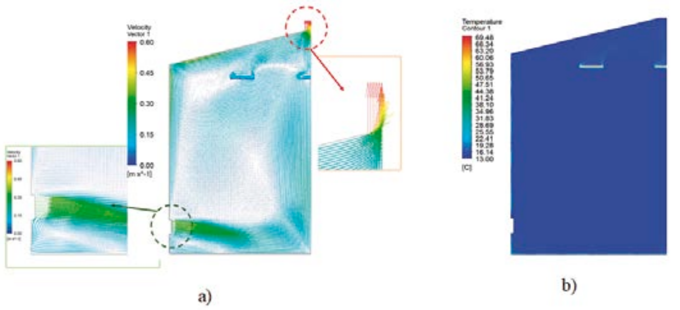

Figure 7 – Case 2: a) Velocity vectors: *t* = 700 s; b) Contours indoor temperature: *t* = 700 s

Figura 7 – Caso 2: a) vettori delle velocità: t = 700 s; b) Profili di temperatura dell'aria interna: t = 700 s

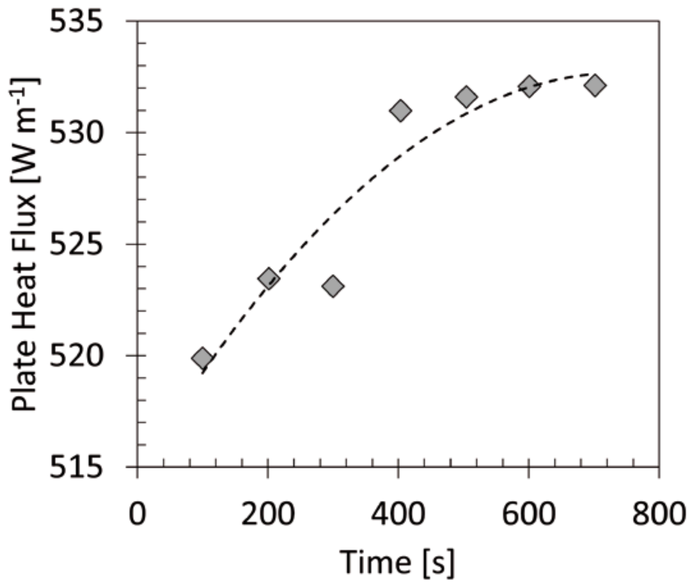

Figure 8 – Case 2, specific thermal power exchanged by the water strip

Figura 8 – Caso 2, potenza termica specifica scambiata dalla termostriscia

specific heat flow exchanged over time by the single plate reached an almost constant value. The latter is equal to about 400 W m^{-1}: at 800 s a value of 399 W m^{-1} is returned, at 1200 s 397 W m^{-1}, that is, a deviation of 0.5%.

The air temperature and velocity fields for case 1 were investigated as well. The analysis was conducted assuming an initial temperature (t = 0 s, inactive plate) of 15 °C (Figure 4a). After the activation of the water strip system, a stratification of temperature is created inside the industrial shed due to natural convection: the air closest to the work area reaches a temperature around 15.50 - 17.50 °C, whereas the air closest to the radiant plates is around 24-26 °C (Figure 4b). At the same time, the natural convection induces a continuous local mixing of the air that is more intense near the hottest surfaces (Figure 5). In the stratified zone at higher temperature, a speed of 0.33 m s^{-1} can be reached.

In the case of forced convection (case 2), Figure 6 shows the flow field with the activation of the water strip plates. After 700 s, it can be said that the flow is completely stabilized. The air exiting at a constant speed from the outlet causes external air to be sucked inside the building. The air flow tends to rise in the symmetrical section of the shed due to the suction of the tower on the roof. The obstacle due to the presence of the radiating plates forces the air to divert its trajectory (Figure 6b and c).

In Figure 7a, the speed vectors oriented towards the right near the inlet, indicating the entry of fresh air, and vectors oriented upwards near the outlet, indicating the air outlet, are reported. Due to the continuous air exchange, the temperature inside the plant tends to uniform around a value of 15-16 °C (Figure 7b).

It is worth to observe that, in terms of the specific power exchanged by the water strips in conditions of constant air flow, a value just over 530 W m^{-1} is reached (Figure 8). This value is approximately 33% higher than that estimated for case 1 (Figure 3).

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Conclusions

The CFD analysis here reported studied the effect of air circulation on the thermal performance of water strips in an industrial building due, for example, to the presence of a ventilation system.

Two case studies were modeled and simulated. The first analyzes the performance of the plates in the presence of natural convection only, in a closed environment without any air exchange. This case has the purpose of defining the reference performance. Case 2 is set up to analyze the effect of introducing a constant flow of external air inside the same shed. The numerical results for the studied configuration confirm that the presence of a constant air exchange leads to an improvement of more than 30% in the performance of the water strip system.

It is reasonable to think that other situations of real operation of the system in industrial sheds (such as the opening of doors, windows or skylights, the presence of hoods or ventilation towers for internal air, and the temperatures of the internal surfaces that are not uniform and certainly lower than that of the internal air) can lead to a considerable increase, in the order of 30% - 40%, of the yield of the water strips compared to the nominal data declared in compliance with the operating conditions according to the EN14037 standard.

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