Thermal insulation of a flour mill to improve effectiveness of the heat treatment for insect pest control

S.M.C.Porto*, F.Valenti , G.Cascone , C.Arcidiacono

(*University of Catania, Agriculture, Food and Environment (Di3A) Building and Land Engineering Section, via S. Sofia 100, 95123, Catania, Italy*)

Abstract: One of the major problems that occur in flour mills, and more generally in industries for food storage and processing concerns the control of insect pests. Insects can multiply under favorable conditions and become responsible for contamination that can determine the non-conformity of productions to the norms and regulations of food quality.

An alternative to chemical treatments for the control of insect pests in flour mills is represented by methods based on heat treatment of the indoor environment. The heat treatment consists in raising the temperatures of the surface where the insects live by increasing the air temperature inside the building. The optimum air temperature for heat treatment effectiveness ranges between 45 ℃ and 55 ℃ and has to be maintained for a period of 36-48 h in order to eliminate all life stages of insect pests for both dehydration and irreversible alterations in lipid and protein levels.

The most widely used system for heat treatment in flour mills is based on heaters powered by electrical energy which are usually integrated with fans to ensure a uniform air temperature inside the buildings.

The objective of this research was to analyze the heat transfer of a number of building elements of a flour mill located in Eastern Sicily (Italy) in order to highlight weaknesses in building thermal behavior. The analysis of building materials and components (e.g., floors, external walls, windows, pillars and beams) and the monitoring of the microclimatic parameters inside and outside the building before and during the heat treatment revealed that relevant heat losses occurred across thermal bridges. On the one hand, thermal bridges represented a weakness of the thermal treatment since insects found refuge in areas of the building where the surface temperatures are lower; on the other hand they caused a huge expenditure of electrical energy in order to maintain indoor air temperature within the optimal range. Therefore, the building components which determine the thermal bridges were analyzed with the aim of studying the contributions of different insulation materials on heat loss. Simulations were carried out by analyzing different insulation solutions to quantify heat loss reduction and possible solutions were proposed in this paper.

Keywords: Thermal bridges, energy efficiency, environmental impact, insulating materials, temperature distribution, thermal transmittance

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1 Introduction

Within the grain supply chain, products quality of flour milling industry, which places between agricultural production and food industry, is likely to affect quality of the products derived from further processing (e.g., bakery products, bread and pasta) (Campolo et al.,2013; Akdogan et al.,2005).

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***Corresponding author: Porto, S.M.C.,** University of Catania, Department of Agri-Food and Enviromental System Management (DiGeSA), Building and Land Engineering Section, Italy. Email: siporto@unict.it

It is well known that flour mill products constitute an ideal substrate to enhance growth of various species of pests such as arthropods, rodents and microorganisms. The presence of these pests determines in turn a quality reduction of the flour milling industry products with negative consequences on their marketing.

For several years before its use was banned by the Montreal Protocol because of its responsibility in reducing the ozone layer, methyl bromide was utilised for disinfestation of grain storage and flour milling processing rooms.

Researchers and operators of the flour milling sector have investigated the possibilities of adopting techniques alternative to methyl bromide for insect pest control in the flour milling factories and integrated pest management (Fields et al., 2002; Suma et al., 2014). Nowadays, the most frequently used treatments for insect pest control in flour mills involve the utilisation of residual insecticides and phosphine fumigation. However, chemical residues contained in the flour milling products and resistance of some pests to several pesticides and fumigants have encouraged utilisation of disinfestation methods alternative to those currently utilised (Mahroof et al.,2005;Campolo et al.,2013).

Among these treatments, the heat treatment of grain storage and processing rooms is an environmentally-friendly method for insect pest control in flour mills since it does not require the use of toxic substances (Tilley et al., 2007).To obtain an effective insect pest control, this method requires increasing of air temperature within the treated environment between 45 ℃ and 55 ℃ - 60 ℃ and maintaining high air temperature levels for a time interval between 36 and 48 h by using electrical or gas fan heaters, with the aim of eliminating all the insect vital stages (e.g., eggs, larvae, adults)(Fields, 1992; Dowdy et al., 1997; Dowdy, 1999; Dowdy and Fields, 2002; Eustace et al.,2003).Insects mainly die for dehydration which occurs at air temperatures higher than 45 ℃ and also for a series of irreversible alterations of the organisms related to lipidic composition, protein coagulation, and elimination of body enzymes.

However, effectiveness of the heat treatment also depends on the surface temperature level reached in the treated areas and the capability of maintaining these temperatures for a suitable time interval (Belda et al., 2011).

Moreover, during the heat treatment an uneven temperature distribution in the different areas of the treated production environments generally establishes. This is mainly due to the building characteristics of the materials and construction elements of the building and due to the presence of equipment that modify the heat fluxes. Therefore, some areas of the treated environments mayresult below or excessively above the lethal temperatures of insects (Dowdy, 1999). On one hand, very high temperatures may damage those devices that are more sensible to heat (e.g., plan sifters, electrical panels, and rubber lining), on the other hand, low temperatures are likely to make the treatment ineffective since cold areas represent the main escape for insects that, as a consequence, would survive to the treatment.

Since it is more difficult to reach insect lethal temperatures in specific areas of the building, such as room corners and contact surfaces between floors and walls, where there is an inadequate air movement and, therefore, an insufficient increasing of surface temperatures by convection, during the heat treatment fan heaters are utilised to facilitate heating of colder areas of the treated environments and allow for a more uniform air and surface temperature distribution (Eustace et al., 2003).

In this work the thermal behaviour of storage and processing room of a flour mill was analysed before, during and after the heat treatment for disinfestation.

A preliminary analysis of the building thermal behaviour showed that the use of fan heaters was not sufficient to guarantee a uniform distribution of surface temperatures (data not shown). Critical points for heat loss were found in thermal bridges, i.e., areas of the building where thermal flux density is higher than in the adjacent building elements due to lack of homogeneity of materials or geometry.

On this basis, the present study aimed at improving thermal performance of the building environment under study by carrying out simulations of suitable interventions on the building components of the treated environments in order to reduce heat losses due to thermal bridges (Asdrubali et al., 2012; Brás et al., 2014).

Within the research field which regards the environmental control and safety of the flour milling industry, the novelty of this study relies on both the analysis of thermal bridges during the heat treatment of the flour mill processing rooms and the suggestion of possible insulation solutions compatible with the considered production environment.

2 Materials and methods

2.1 The mill under study

The flour millshave geometrical, distributive and functional characteristics that differ from those typical of other agro-industrial buildings. The grain processing plants for flours and sub-products production, which are composed of the milling plant and complementary structures such as silos, warehouses and service rooms, have wide linked volumes at different levels and machinery connected at the different floors by vertical ducts which carry semi-finished goods from lower floors to the higher ones and vice versa, following the production process.

The present study was carried out in a milling plant located in Eastern Sicily (Italy).

The building, which was built in the 70's, has four floors on a rectangular plan with the longitudinal axis oriented in the East-West direction (Figure 1).

(a) (b)

Figure 1 Views of the flour mill where the heat treatment was carried out: a) North façade and b) South façade

The grain and flour storage rooms have a bearing structure made of reinforced concrete walls. The rooms for grain processing, instead, have a reinforced concrete framed bearing structure (beams, pillars and floors) and brick perimeter walls.

2.2 The heat treatment

The heat treatment, which was carried out on April 2014, was applied in all the building floors to both the storage and the processing rooms. The thermal behaviour of the building was monitored at the third floor above the ground floor of the milling plant (Figure 2). This floor was chosen for the presence of equipment that is particularly sensible to high temperatures, i.e., the plan sifters, which have sieves stuck to wooden frames by glue.

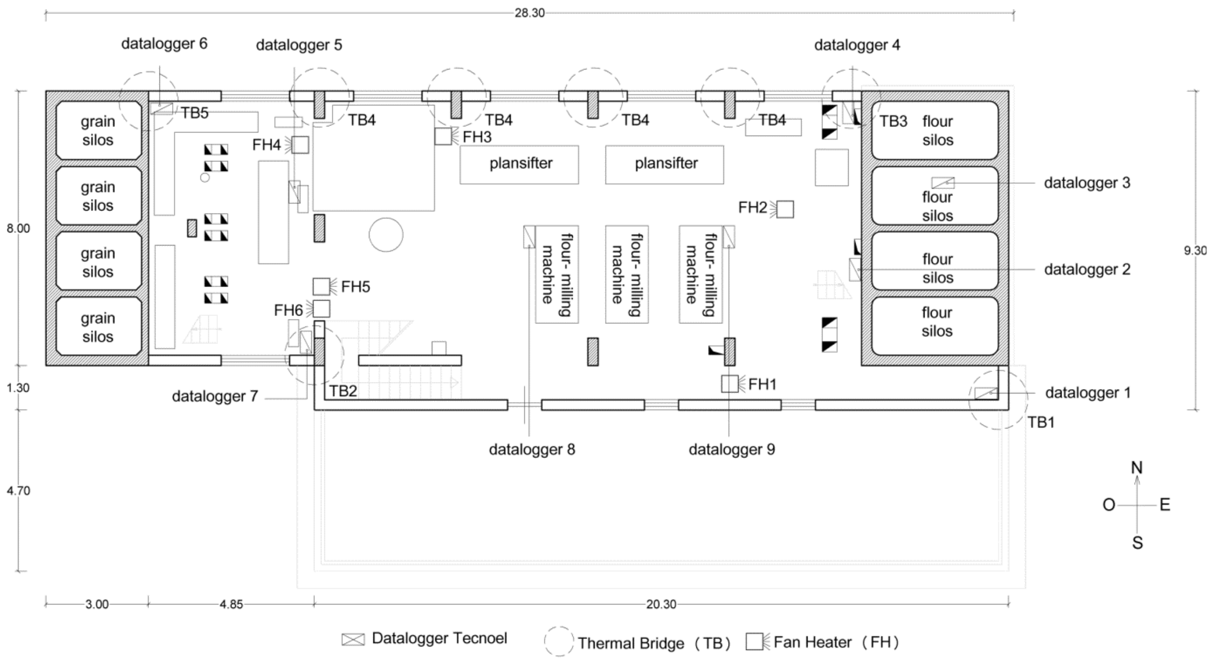

Figure 2 Plan of the third floor of the mill under study where the positions of both fan heaters(FH) and data loggers are showed. Dashed circles highlight the locations of thermal bridges (TB)

In the considered floor, the heat treatment involved the use of six fan heaters (Figure 2) set at a temperature of 70℃ and providing a ventilation capacity of 2500 m^3/h.

During the heat treatment the temperatures and relative humidifies inside and outside the building were measured by means of data loggers. Specifically, air temperature and relative humidity were recorded by nine Grillobee data loggers manufactured by Tecnoel (Italy) which were connected to sensors (transducer by Rotronic Italia srl, Italy).The air temperatures were measured by sensors placed at a height of 10 cm above the floor (Figure 2), near the thermal bridges. Moreover, another sensor was located inside one of the flour silos. All the flour silos were empty during the heat treatment. All the variables were measured by the data loggers before, during and after the heat treatment at 15 second time intervals averaged every half an hour. The surface temperatures of the building components of the thermal bridges were measured by using a thermal camera (ThermaCamB2, FLIR system inc., USA).

The heat treatment started at 00:00 of 19 April 2014 and ended at 00:00 of 21 April 2014. During the heat treatment different typologies of thermal bridge were identified by using the thermal camera (Figure 3). Specifically, a survey was carried out during the heat treatment at about 5:00 p.m. of April 19, 2014, when the monitored air temperatures reached a stationary thermal state. Figure 2 reports only one thermal bridge for each typology.

2.3 Thermal bridge analysis

When a thermal bridge is present ina building component of the building envelope, an increase of heat flux density and a decrease of the surface temperature occur in it. Computation of the heat flux due to a thermal bridge can be accurately performed by utilising numerical methods according to the recent international standards EN ISO 10211-1 and EN ISO 10211-2, which regard the two-dimensional and three-dimensional computations of heat flux through building thermal bridges, respectively. Moreover, the standard EN ISO 14683 provides computation guidelines for both heat flux and linear heat transmittance (ψ_k) by means of simplified methods (Cudicio M.,2013; International Organization for Standardization, 2008a, 2008b, 2008c, 2008d).

The heat flux Φ that establishes between the indoor and outdoor environments, which are at temperatures $T_i$and $T_e$respectively, is computed by Equation 1:

$$\Phi = H_T(T_i - T_e) \quad (1)$$

The transmission heat transfercoefficient H_T is obtained from the following Equation 2:

$$H_T = L_s + L_U + L \quad (2)$$

in which:

L_s is the ground thermal coupling coefficient that is determined according to the EN ISO 13370/2008;

L_U is the heat exchange coefficient in unheated environments, according to EN ISO 13789/2008;

$L$is the thermal coupling coefficient through the building envelope, which is defined by Equation 3:

$$\mathrm{L} = \sum K_i\ A_i + \sum \Psi_k\ l_k + \sum\ \chi_j \quad (3)$$

where:

K_i is the thermal transmittance of the element $i$of the building envelope;

$A_i$is the area of element$i$ of the building envelope where K_i is applied;

$\Psi_k$is the linear heat transmittance of thermal bridge k ;

$l_k$is the length of linear thermal bridge k where Ψ_k is applied;

$\chi_j$is the point thermal transmittance of the point bridge j.

The linear heat transmittance applied$\Psi$is computed by the following Equation 4:

$$\Psi = \mathrm{L}^{2\mathrm{D}} - \sum \mathrm{K_i}\ \mathrm{l_i} \quad (4)$$

in which:

$L^{2D}$is the linear thermal coupling coefficient obtained by a two-dimensional computation of the building component that separates the two considered environments;

$l_i$is the length of linear thermal bridge i where K_i is applied.

In this study, the influence of thermal bridges due to $\chi_j$was neglected because it was not found during the survey.

The analysis of thermal bridges was carried out by using TerMus-PT software (Acca Software, Italy) with the computational solver The BriNA (Thermal Bridge Numerical Analysis). The software allows for the numerical computation of the linear heat transmittance of thermal bridges according to EN ISO 10211 and 14683.

The numerical computation, applied to the specific conditions analysed, provided heat transmittance values more accurate than those achieved by adopting simplified thermal bridges typologies which are available in the EN ISO 14683. In fact, these typologies can be modified only in the characterisation phase of materials while they cannot in the characterisation phase of geometry (ANIT, 2013).

The software utilised for the numerical computation, allowed for the assessment of the thermal bridges analysed by applying the definition contained in the Italian Standard (Legislative Decree 192/2005; Legislative Decree 311/06), which states that a thermal bridge is 'corrected' when the following Equation 5is satisfied:

$$\Phi - \Phi_{wTB} < 15\%\ \Phi \quad (5)$$

where Φ is the heat flux through the considered thermal bridge and Φ_{wTB} is the heat flux through the dummy wall, i.e., a portion of the wall where the thermal bridge exists, which is composed of the materials of the actual wall.

In this study the thermal analysis of TB4 was excluded since its typology belongs to the simplified cases contained in the EN ISO 14683 and thus the numerical analysis is not needed to determine the heat flux through this thermal bridge.

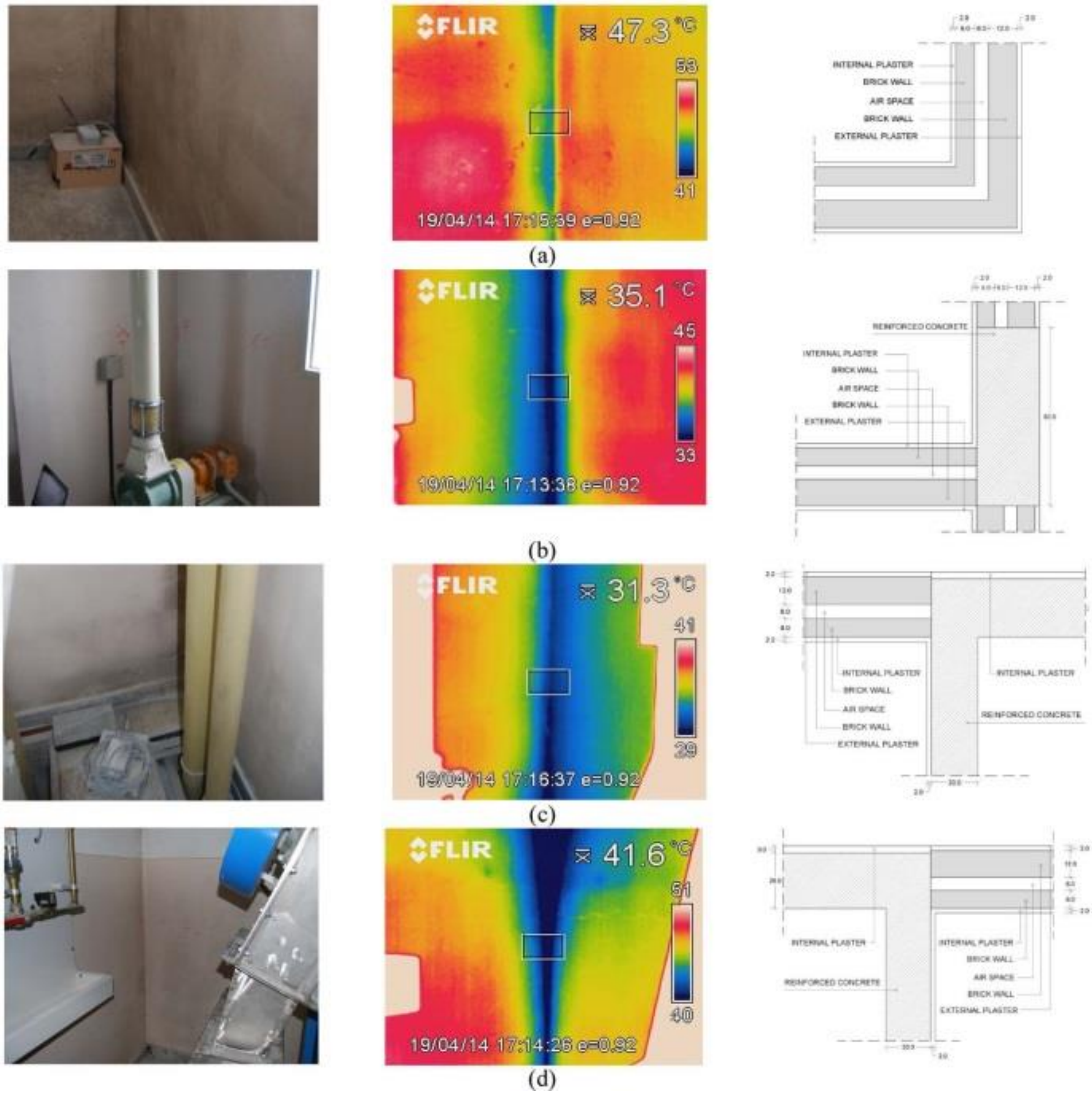

Figure 3 RGB photograph, thermal photograph and horizontal sections of the building components (dimensions are in centimetres) of the thermal bridges analysed at around 5:00 p.m. of 19 April, 2014. a) TB1; b) TB2; c) TB3; d) TB5

3 Results and discussion

In the day previous to the heat treatment (18 April 2014), the average value of the air temperature recorded by the sensors located in the processing room was about 14.0 ℃. The highest temperature of 17.4 ℃ was achieved by the sensor placed inside the flour silos (Table 1).

Table 1 Daily average values of air temperatures recorded by each datalogger one day before (18/04), during (from 19/04 to 20/04) and after (21/04) the heat treatment

Data logger	1	2	3	4	5	6	7	8	9
Day	t [C °]	t [C °]	t [C °]	t [C °]	t [C °]	t [C °]	t [C °]	t [C °]	t [C °]
18/04	14.2	14.4	17.4	14.2	13.5	14.0	13.2	13.9	14.4
19/04	51.4	42.9	36.7	40.0	45.6	46.5	42.9	51.0	44.7
20/04	46.6	59.5	49.5	60.9	55.3	55.6	53.2	57.7	56.8
21/04	33.3	42.0	41.1	41.9	39.8	39.3	41.0	41.5	42.0

Note: data logger 3 monitored the temperature inside flour silos.

During the heat treatment, the average value of outdoor air temperature was 21.5 ℃, whereas the average values of indoor air temperature recorded by the sensors located in the processing room were 45.7 ℃ and 55.7 ℃, for 19 and 20 April respectively. The lowest air temperatures were recorded inside the storage silos on 19 April and near the thermal bridge TB1 on 20 April(Table 1).

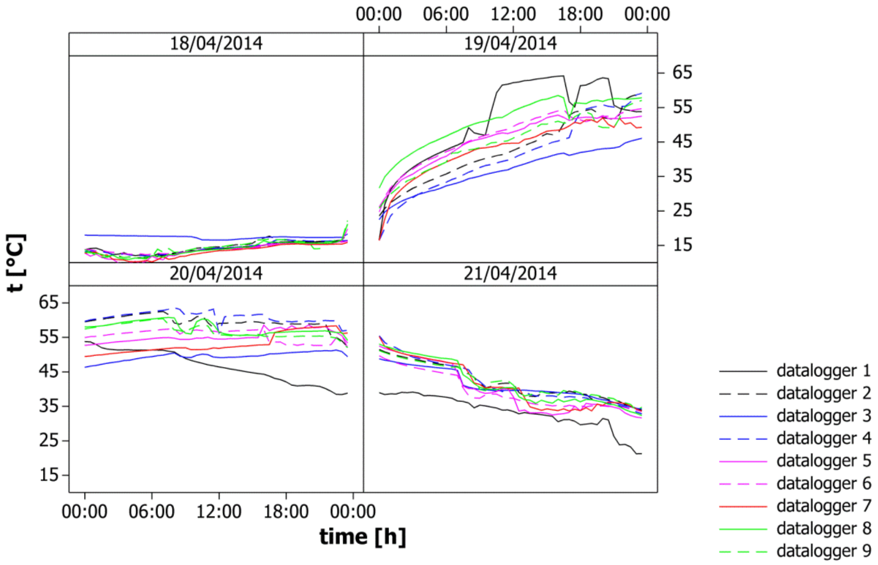

Figure 4 Air temperatures recorded by the dataloggers during the heat treatment

The temperature curves in Figure 4 show some peaks due to the positioning of the fan heaters in front of the sensors for a time interval. In fact, it is common practice among the operators of heat treatment to rotate the fan heaters in order to make temperature distribution more uniform in the treated environment.

In Figure 4, for instance, the air temperature profile recorded by data logger 1 is highly affected by the position of the fan heater FH1(Figure 2) that was placed in the room towards the TB1 during the first hours of treatment. Since the fan heater was rotated at about 8:00 p.m. of 19 April 2014 a decrease of the air temperature curve was registered in the following hours.

A first data elaboration, which was carried out by utilising Termus-PT software, was aimed at finding the value of air temperature that would determine the minimum value of 45 ℃ for wall and floor surface temperatures of the considered thermal bridges. This value of air temperature is the value that has to be reached for guarantee a suitable insect pest control in the areas near the thermal bridges. From this data elaboration it was found that this value of indoor air temperature should have been equal to about 53.5 ℃.

The mean values of the daily average air temperatures (T_{i_mean}) recorded by the data loggers located near the thermal bridges TB1, TB2, TB3 and TB5 (Table 2), demonstrated that within the 48 hours of treatment the average temperature of the air inside the treated environment did not reach 53.5 ℃. Therefore, wall and floor surface temperatures of the thermal bridges (T_s) were unsuitable to guarantee the control of insects as they resulted lower than 45 ℃ in the simulations (Table 2).

Table 2 Daily average temperatures in the two days of treatment, mean values of the daily average air temperatures (T_{i_mean}) and wall surface temperatures of the thermal bridges (T_s) that were recorded by the data loggers near thermal bridges TB1, TB2, TB3 and TB5

	TB1 t [C °]	TB2 t [C °]	TB3 t [C °]	TB5 t [C °]
19/04	51.4	45.6	40.0	46.5
20/04	46.6	55.3	60.9	55.6
T_{i_mean}	49.0	50.5	50.5	51.1
T_s	41.8	43.5	43.3	43.5

The practice to direct fan heaters towards the thermal bridges, which is widely used by operators, isgenerally apt to guarantee the effectiveness of the heat treatment. In fact, this solution proved to be suitable forTB1 which was subject to air temperatures higher than 53.5 ℃ until the first hours of the second day of treatment (Figure 4, see datalogger1) when the fan heater FH1 was moved. However, increasing the number of fan heaters in order to direct one fan heater towards each thermal bridge is neither economically viable (Chinnici et al., 2014) nor technically feasible due to building and equipment constraints.

When fan heaters are not directed towards the thermal bridges an extension of the heat treatment duration for more than the 48 h considered should be required. However, it would cause an increase of both energy costs of the treatment and risk of damaging the machinery installed in the treated environments.

Therefore, for TB2, TB3, and TB5 building interventions on thermal bridges could be a suitable solution to improve their thermal performances with the aim of reducing the heat flux through them.

Corrective interventions, which would result compatible with the use of the storage and processing rooms and the technical choice of applying the insulation on the internal side of the wall, were proposed by evaluating different insulating materials on the basis of their characteristics, e.g., transpiring capacity, heat conduction, crushing resistance, and adaptability to the building materials and structure.

Among the different typologies of insulating materials analysed, those which could be placed on the internal side of the walls were considered and, among them, the materials that have low thermal conductivity (and thickness. On the basis of these analyses, two different interventions were proposed:

- intervention a): application of a coating made of Spaceloftnano-porous Aerogel sheet(= 0.013 *W/m K*, *t* = 16 mm), which costs around 55 €/m^2 (labour costs excluded).
- intervention b): application of an insulating natural plaster, which is transpiring, dehumidifying and prevents condensation (= 0.056 *W/m K*, *t* = 20-30 mm). Its cost is estimated to be about 35 €/m^2 (labour costs excluded).

In order to compare the performances of these two interventions, simulations were carried out by considering the same conditions with regard to internal and external air temperatures. The results of the simulations (Table 3) demonstrated the increase of surface temperatures T_s and, as consequence, a decrease of heat fluxes Φ through the considered thermal bridges.

Table 3 Parameters obtained by the numerical computation.

	TB2			TB3			TB5		
	without correction	intervention a)	intervention b)	without correction	ntervention a)	intervention b)	without correction	intervention a)	intervention b)
ψ [W/mK]	0.39	-0.73	-0.29	3.13	1.16	1.57	3.21	1.61	2.59
Φ[W/m]	76.67	53.74	62.96	51.79	23.42	22.59	51.08	16.16	16.51
L^{2D}[W/mK]	3.30	2.21	2.65	3.69	1.72	2.13	3.81	2.21	3.19
l_i[m]	2.84	2.86	2.86	0.53	0.53	0.53	0.57	0.57	0.57
Φ_{wTB}[W/m]	63.41	63.74	63.74	16.41	16.41	16.41	17.72	17.72	17.72
T_s[C °]	43.5	48.3	45.8	43.3	48.5	46.8	43.5	48.8	47.5

By comparing the values of the heat fluxes *Φ* reported in table 3 for each thermal bridge and for each type of intervention with those related to thermal bridges without correction, it was demonstrated that the application of Spacel of tnano-porous Aerogel sheets (intervention a) allowed for a reduction of heat fluxes *Φ* of about 30%, 55%, and 68%, for TB2, TB3, and TB5, respectively (Table 3).Flux reductions through the considered thermal bridges which were determined by utilising the insulating natural plaster (intervention b), were about 18%, 56%, and 68% for TB2, TB3, and TB5,respectively.

The comparison among the heat flux reductions which were obtained by applying the proposed building interventions showed that for TB2 the intervention a) was more effective than intervention b) without increasing plaster thickness and treated surface areas (Figure 5).

For TB3 and TB5 the effectiveness of both interventions was similar in terms of surface temperatures and heat flux reductions. This outcome was achieved by increasing plaster thickness and treated surface areas in order to obtain the thermal bridge correction as established by relation (5). The increases of plaster thickness as well as treated surface areas are technically feasible and economically viable because the increase of cost due to plaster purchase and its laying is small compared to the cost of Spacel of tnano-porous Aerogel sheets.

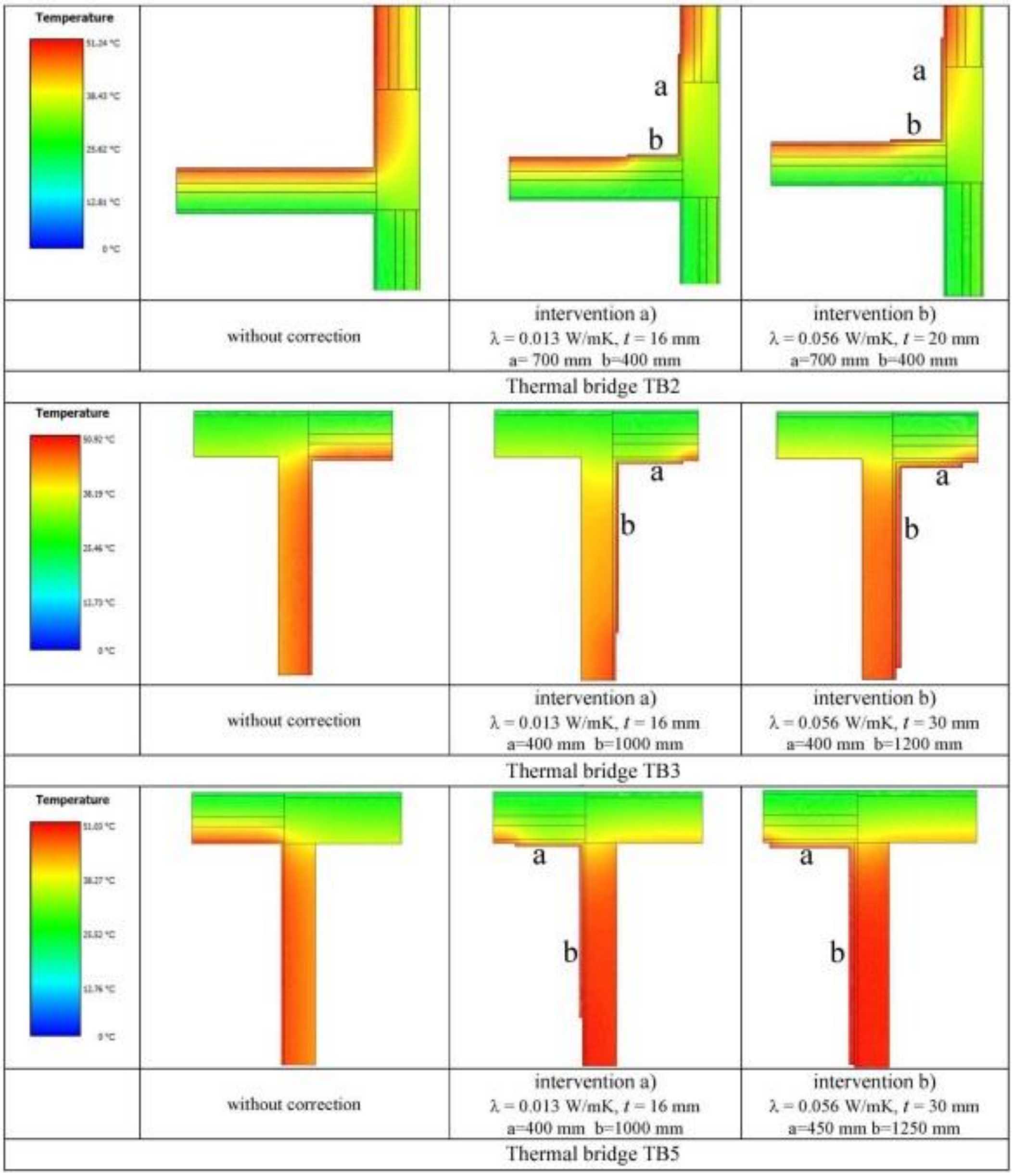

Figure 5 Comparison between the isothermal curves obtained before and after the building interventions on thermal bridges.

4 Conclusions

The heat transfer of a number of building elements belonging to a flour mill located in Eastern Sicily (Italy) were analysed in order to highlight the weaknesses of the building thermal behaviour before and during the heat treatment for disinfestation of insect pests.

The aim of improving thermal performance of the building environment considered was achieved by carrying out simulations of suitable interventions on the building materials of the treated environments in order to reduce heat losses due to thermal bridges.

Simulations outcomes by using different insulation solutions allowed for quantifying heat loss reduction in the range from 18% up to 68%. In some cases, the use of Aerogel sheet solution was found to improve heat loss reduction with a minor thickness in comparison to the use of natural plaster. However, natural plaster remains the cheaper solution with an acceptable thickness and a good heat flux reduction.

Further improvements of the research could involve other analyses on thermal bridges aimed at comparing the actual wall condition with that modified by wall insulation laidin the wall air space.

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