CO-HEATING TEST AND COMFORT ASSESSMENT OF A COUPLED SYSTEM MADE BY A VENTILATED WINDOW AND A HEAT RECOVERY UNIT

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ABSTRACT

The article describes the results of an experimental campaign carried out at ITC-CNR in outdoor test cells to evaluate the energy performance and the related comfort level achieved through a coupled system made up of a dynamic window and a heat recovery unit.

The test was carried out on two calibrated test cells with the same geometric, constructive and thermo-physical characteristics. They were appropriately monitored, throughout the year 2013. In the reference cell, called C2, a traditional window with double glazing, aluminium frame and indoor blind was installed, while the air circulation was provided by a centrifugal extractor. In the second one, called C3, a dynamic window with integrated blind was installed and the air circulation was provided by a heat exchanger. The air conditioning systems consist of electric heaters in winter and heat pumps in summer.

The different operating configurations allowed the trends of the dynamic system to be assessed in two different phases: analysis of seasonal energy behaviour and analysis of the thermal comfort conditions.

The first phase consisted in the assessment of the energy consumption of the two test cells using the co-heating methodology. The results showed an overall lower consumption of C3 compared to C2, both in winter and in summer, with 20% and 15% peak energy savings, respectively. The results were also confirmed by the analysis of Energy Signature.

During the second phase, the psychrometric analysis was introduced to better understand the complex heat fluxes management actions carried out by the dynamic window-heat recovery integrated system: action of heat recovery unit; dual action to reduce heat transfer in the dynamic window; air pre-heating action by the dynamic window, before entering in the exchanger.

The transformed patterns confirmed the positive synergy during the winter season (maximum yield equal to 1.9), while, for the summer season, they provided a clear interpretation of the better operation of the system only with the heat recovery unit turned on (average yield minimum of 0.7).

The analysis of the PMV and PPD indices showed that, when the maximum solar radiation is less than 600 W/m2, the C3 recorded a slightly higher PPD. With average external temperatures equal to about 20 °C and maximum solar radiation of approximately 900 W/m2, the values of PPD and PMV of the two cells were equivalent. When the dynamic glass was turned off and only the recovery unit worked, the C3 provided the best comfort conditions.

Finally, the Fusion Tables, a web service provided by Google, were used to extend the results to the Italian provinces taking into account the standard monthly climate data. It was showed that with decreasing latitude, the energy savings of the combined system increased and reached the maximum value calculated for cities located in the south.

KEYWORDS

Dynamic system, ventilation, heat recovery, co-heating, thermal comfort

1 INTRODUCTION

This article describes the results of an experimental campaign carried out on a dynamic window, called VetroVentilato®, consisting of a ventilated window connected to a heat recovery unit. The system is an evolution of a previous configuration consisting of just the ventilated glass (Lollini et a., 2012) that showed a good energy behaviour compared to a traditional configuration.

The experiment, carried out on two test cells, involves two phases: the former aimed to analyse the energy savings due to the installation of the dynamic system, the latter aimed to assess the indoor thermo-hygrometric comfort. In particular, in the first phase, the energy savings have been assessed in terms of cumulated consumption and the Energy Signature method (Belussi and Danza, 2012) has been applied, aimed to assess the energy behaviour of the dynamic system under variable external climatic conditions.

2 EXPERIMENTAL CAMPAIGN AND CO-HEATING TEST

The experiment includes two external test cells with the same dimensional and thermo-physical characteristics, properly calibrated and equipped with the appropriate monitoring devices (Stamp, 2012). The dynamic system has been installed in one cell (hereinafter C3), while a window with a traditional double-glazing has been installed in the other cell (hereinafter C2). The experiment was carried out with different configurations, as shown in Table 1.

Table 1: Configurations

Code	Heating	Cooling	Dynamic window	Heat exchanger	Flow Rate
Heat 1	**On**	Off	**On**	**On**	45 m^3/h
Heat 2	**On**	Off	**On**	**On**	60 m^3/h
Heat 3	**On**	Off	**On**	Off	-
Cool	Off	**On**	**On**	**On**	45 m^3/h
Comf 1	Off	Off	Off	**On**	45 m^3/h
Comf 2	Off	Off	**On**	**On**	45 m^3/h

2.1 Brief description of the dynamic system

The dynamic system consists of a ventilated window connected to a traditional heat recovery unit placed above the window. The window consists of a double-glazing (3+3-16-3) and an internal micro-drilled blind placed 2 cm from the glass so as to create an internal air gap. The exchanger is connected to the dynamic system so the indoor inlet flow allows the air to be drawn from the air gap.

The operation of the combined system allows the air of the internal environment to be got in the air gap, the air pre-heats thanks to the solar radiation and the heat is recovered by the exchanger before being ejected. The heat recovered is used to heat/cool the air from the outdoor (Figure 1a). In C2, a centrifugal extractor is placed on the north wall (Figure 1b).

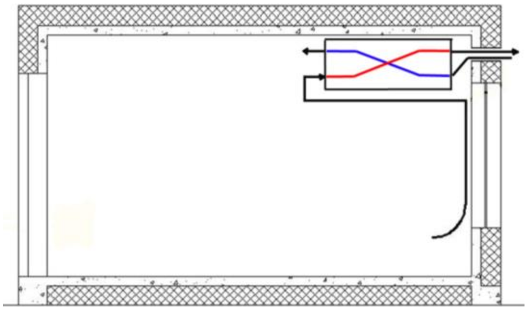

Figure 1a: Test cell section - ventilation with heat recovery

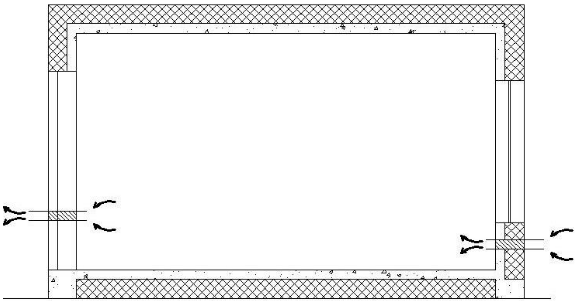

Figure 1b: Test cell section - direct extraction

3 FIRST PHASE: THE ASSESSMENT OF THE ENERGY CONSUMPTION

The first phase of the experimental campaign consists of the analysis of the energy consumption of the two test cells aimed to assess the energy performance of the dynamic system compared to a traditional double glazing. In particular, the energy consumption has been analysed following two approaches:

- comparison of the cumulated consumption;
- comparison of the Energy Signature of the test cells.

In this article, the Energy Signature method has been used in an alternative way compared to that described in Annex B of the international standard EN 15603:2008. Normally, in fact, the Energy Signature is used to assess the energy consumption and consequently the energy behaviour of a building. In this article, instead, the method is used as an indirect empirical tool to assess the energy performance of the dynamic system. Cumulated consumption and Energy Signature have been evaluated in the period shown in Table 2.

Table 2. Heating and cooling period

Code	Period
Heat 1a	07/01/14 - 11/02/14
Heat 1b	04/04/14 - 30/04
Cool	01/07/13 - 21/07/13

3.1 Consumption and energy savings

The analysis of the cumulated consumption allows the energy savings to be identified due to the dynamic system in a given period, compared to the consumption of C2.

Configuration "Heat" (a+b)

Figure 2a and 2b show the consumption trend (red and blue lines) of the two test cells and the mean daily percentage difference detected in the configuration "Heat 1" (a+b). The overall energy consumption of C3 is constantly lower than that of C2, in both the periods. In particular, in the configuration "Heat 1a" the consumption of C3 is on the average 18% lower than C2 (dotted line in Figure 2a), with a final difference equal to 109 kWh. In the configuration "Heat 1b", characterized by higher temperatures, the energy behaviour of the test cells diverges to a greater extent and the mean percentage deviation increases up to about 30% with peaks exceeding 40% (Figure 2b).

This trend is explained by observing in more detail the absolute consumption values of the test cells: the greatest energy savings, in absolute value, and the lowest percentage deviation are detected in the first, cooler, period; vice versa, the lowest energy savings, in absolute value, and the greatest percentage deviation are detected in the second, warmer, period.

The dynamic system allows a lower utilization of the heating plant, in the warmer period.

The increase of the ventilation rate, as in configuration "Heat 2", determines the increase of the percentage deviation of the two test cells.

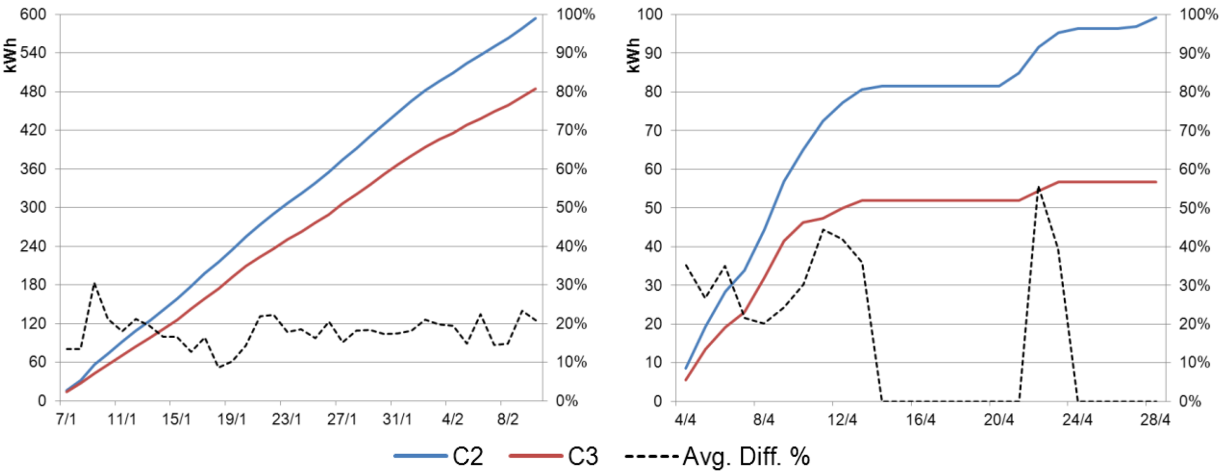

Figure 2a: Cumulated consumption configuration "Heat 1a"

Figure 2b: Cumulated consumption configuration "Heat 1b"

Configuration "Cool"

Figure 3 shows the trend of the cumulated consumption of the test cells in the "Cool" configuration. C3 shows the best energy behaviour and the lowest consumption, in percentage terms (about 13%) and in absolute terms (about 25 kWh) than C2. However, in the cooling phase, the combination of the dynamic system and the heat recovery unit does not allow the flux to be optimally managed, because exhaust air that comes into the exchanger from the indoor environment transfers heat to the inlet air, heating it.
In the cooling season, the reduction of the consumption is due only to the dynamic glazing.

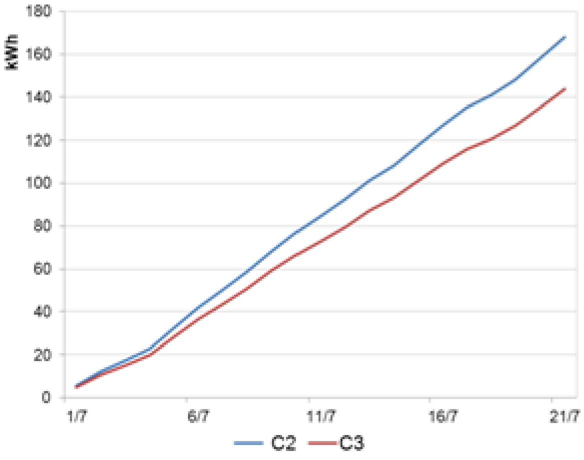

Figure 3: Cumulated consumption configuration "Cool"

3.2 Energy Signature

The Energy Signature has been applied in order to determine the energy behaviour of the dynamic system when the external climatic conditions vary. The Energy Signatures of the two test cells have been compared in the different configurations. The contribution of the dynamic system to the overall performance of C3 could be assessed thanks to this method.

Configuration "Heat"

The comparison of the Energy Signatures in the configuration "Heat 1a" (Figure 4a) shows a better energy behaviour of C3 than C2, confirming the performance of the dynamic system both in terms of heat losses (related to the slope of the straight lines) and in terms of switch-off temperature of the heating system (intersection of the straight line with the x-axis). The slope and the switch-off temperature of C3 are about 3.5 W/K and 2°C lower than those of C2, respectively.

The same reasoning can be made for the configuration “Heat 2”. Figure 4b shows how the energy behaviour of C3 is further improved than that of C2. This is due to the performance of the two single components, dynamic glazing and heat recovery unit, which are more efficient with the increasing of the airflow rate. In C3, the increasing of the airflow rate, that involves greater ventilation losses, is balanced by the combined action of the dynamic system. In C2, the ventilation losses are not recovered, with a consequent increasing of the overall consumption.

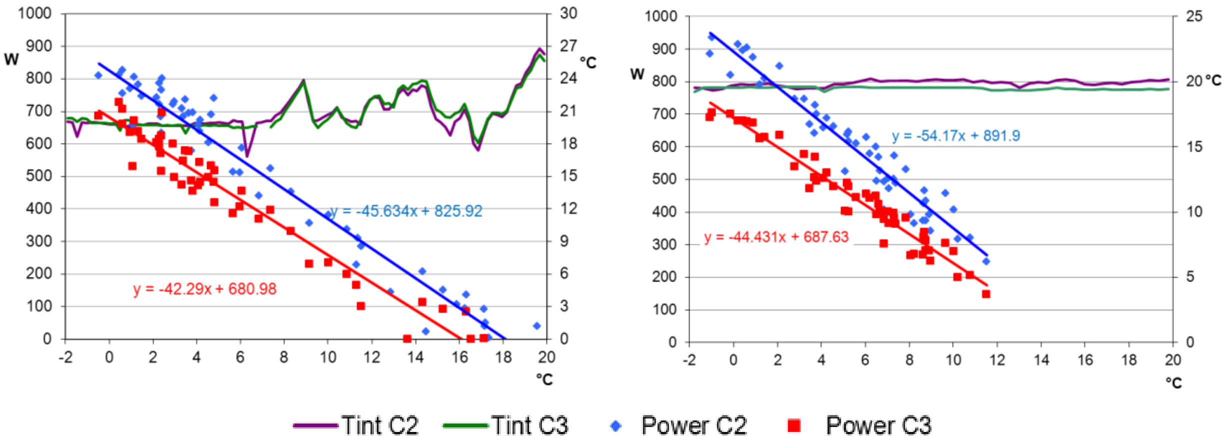

Figure 4a: Energy Signature configuration “Heat 1 (a+b)” - comparison

Figure 4b: Energy Signature configuration “Heat 2” - comparison

Configuration “Cool”

Similarly to the winter situation, it is possible to analyse the dynamic system behaviour in summer through the Energy Signature.

The outcome of the cumulative consumption analysis is confirmed by the assessment of the Energy Signature. The comparison, in fact, shows both a lower slope and a downward translation of the Energy Signature of C3 with respect to C2, due to a better management of the thermal loads of the combined system compared to the reference one.

Thus, also in summer, the dynamic system has the best energy behaviour.

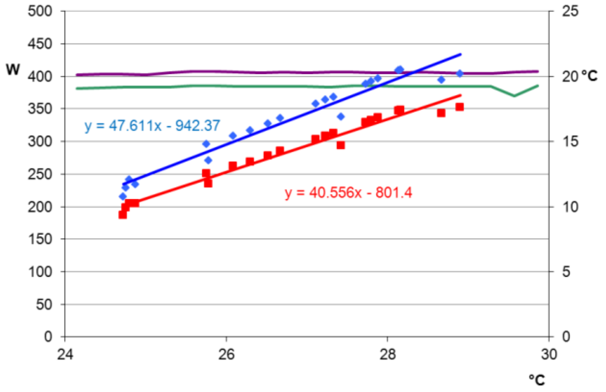

Figure 5: Energy Signature configuration “cool” - comparison

3.3 Extention of results

The Energy Signature method allowed the slope and the constant term of the straight lines of the test cells to be identified. Taking into account the average monthly temperature, it is possible to extend the obtained results to the whole Italian territory, using an experimental approach, aimed to theoretically assess the energy behaviour in different climatic conditions.

In this article, and by way of example, two configurations are considered: “Heat 1” and “Heat 3”. The mapping has been applied to all the Italian provinces.

Starting from the external temperature data and the Energy Signature equations (see Figure 4a), the theoretical consumption of the cells and the percentage difference of consumption between the two cells, C2 and C3, are calculated.

Five classes, each characterized by a specific colour, have been identified as a function of the energy savings guaranteed by the dynamic system, compared to the reference system.

The two resulting thematic maps (Figure 6 and Figure 7) allow the two cases to be compared and the average energy savings to be evaluated. From configuration “Heat 3” to “Heat 1”, the following savings are possible:

- Northern Provinces: from 6.2% to 16.5%;
- Central Provinces: from 9.8% to 19.7%;
- Southern Provinces: form 13.7% to 26.5%.

The warmer the conditions, the greater the saving.

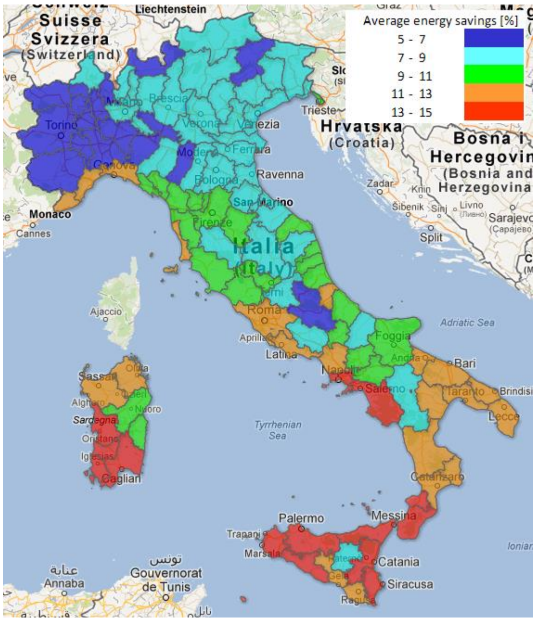

Figure 6: Thematic map - “Heat 3”

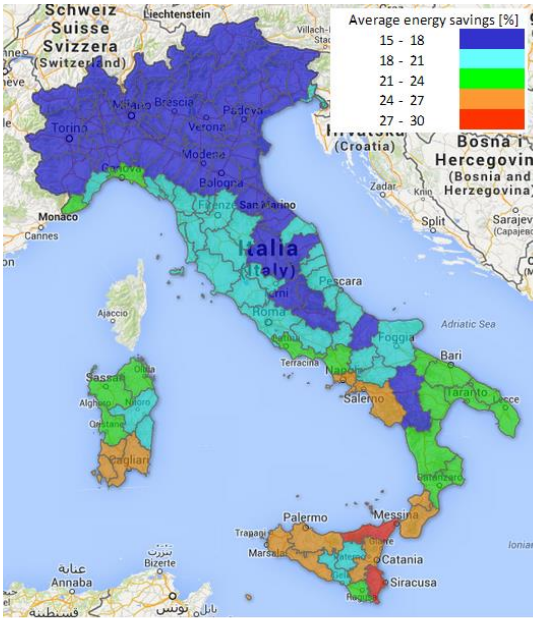

Figure 7: Thematic map - “Heat 1”

4 SECOND PHASE: THE EVALUATION OF INDOOR IGRO-THERMAL CONDITIONS AND COMFORT

4.1 The psychrometric analysis

The current operating logics of the dynamic system play a key role in the management of heat flows, carrying out three different actions. The first takes place at the heat recovery level: the cross-flow exchange of thermal energy between the exhaust air outgoing from the conditioned test cell and the incoming air from the external environment involves a pre-heating action during the winter season.

Then, the transparent component involves a reduction in heat exchanges with the external environment: the air, drawn in by the indoor environment and passing through the ventilated cavity, allows the surface temperature of the inner glass as close as possible to the temperature of the indoor environment to be maintained. This action involves a reduction of the thermal transmittance of the component as a function of the increasing flux in the air gap. At the same time, the integrated preheating action due to the solar radiation hitting the transparent component pre-heats the air that passes through the gap before reaching the recovery unit (McEnvoy et al., 2003).

In this synergic plant context, the psychrometric analyses (ASHRAE 55), particularly focused on the environment line and the straight patterns of the transforms, allow the results of the energy evaluations to be represented and to be interpreted.

Table 3 shows the overall average data efficiency of the two test cells, related to representative detailed analyses.

During the winter testing period, the indoor environmental monitoring data show the positive synergy between the dynamic system and the heat recovery unit, which confirms the energy consumption data. In fact, at constant indoor conditions (Temperature and RH%), C3 shows an average efficiency improvement compared to C2 of approximately 7%.

On the contrary, during the summer, the combined system does not allow to effectively heat flows to be managed.

Table 3: Heating & Cooling configurations

Season & Plant Configurations	**Reference period**	**Reference day**	**DT (C3-C2)**	**D%RH (C3-C2)**	**Avg. Efficiency (C3-C2)**
Heat1	22-29 April 2013	22 April	<1°C	<5%	7% ca
Cool	01-07 July 2013	03 July	≈1°C	≈1%	--

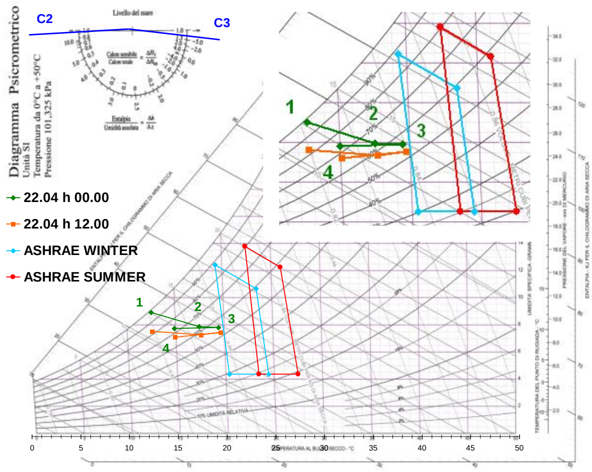

Figure 7: Psychrometric chart related to the operating condition factor and the plant-related transforms for “Heat1” configuration

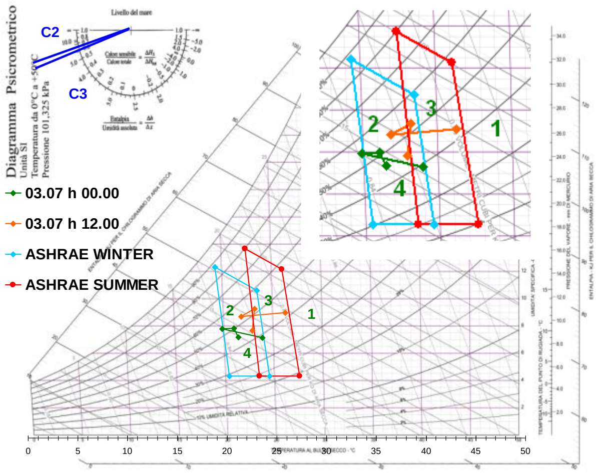

Figure 8: Psychrometric chart related to the operating condition factor and the plant-related transforms for “Cool1” configuration

Figure 7 and Figure 8 show the points of the plant-related transforms:

- point 1 is the inlet airflow from the outside;
- point 2 is the heat recovery unit airflow to the inside;
- point 3 is the intake airflow of the heat recovery unit from the inside, after passing through the ventilated cavity of the glass;
- point 4 represents the heat recovery unit airflow to the outside.

During the winter tests, as shown in Figure 7, the combined operation involves that the slope of the operating condition factor corresponds of the slope of the line connecting points 1-3.
So, the combined system operates in synergy, generating a virtuous cycle in energy savings through the combined action.
Instead, concerning the summer season, the possible considerations are very different.
Even if the indoor conditions in both the test cells are the same, as shown in Table 3, the psychrometric chart in Figure 8 shows how in this configuration the slope of the operating condition factor radically differs from the slope of the line connecting points 1-3. This difference is more evident during direct solar radiation phases.
During winter testing the combined system contributed to the increase of the overall efficiency, allowing to achieve the set point conditions provided for by the indoor environment line with a reduced energy expenditure by the heating system.
The operation of the dynamic window, represented by the segment 2-3 of the orange polyline (Figure 8), involves a daily overheating of the air pre-treated in C3, reducing the heat recovery unit efficiency (1-2 segment). In fact the outgoing air is cooled by the exchanger (3-4 segment).
In the summer season the combined system involves a worse phase shift than expected, which is made evident by the psychrometric chart.

4.2 Comfort analysis

The thermo-hygrometric comfort level of the two test cells has been evaluated using the Fanger method (EN ISO 7730:2006). The analysis has been carried out in the configurations “Comf 1” and “Comf 2”, in different weeks (Table 4).

Table 4: Cases comfort analysis

Code	Period
Comf 1	03/06/13 – 09/06/13
Comf 2	14/05/13 – 24/05/13

Configuration “Comf 1”

In Figure 9, the Predicted Percentage of Dissatisfied values (PPD), calculated assuming a clothing value equal to 0.75 clo, are better in C3 than in C2, with a maximum deviation slightly more than 30%. In Figure 10 the Predicted Mean Vote index (PMV) indicates, in both cells, a thermo-hygrometric sensation average comprised between the “neutral” class and the “slightly warm” class. In C2, higher temperature and humidity values are detected.

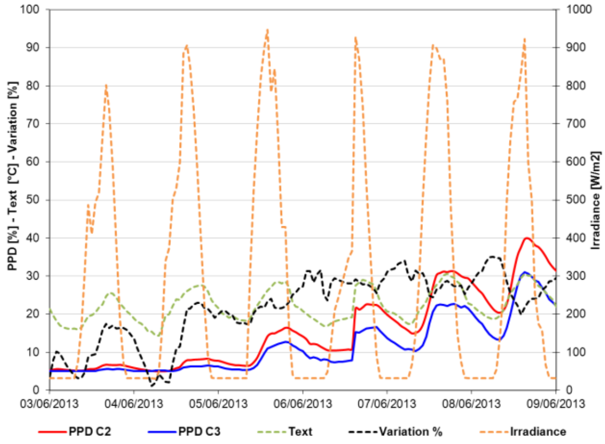

Figure 9: PPD trend - “Comf 1”

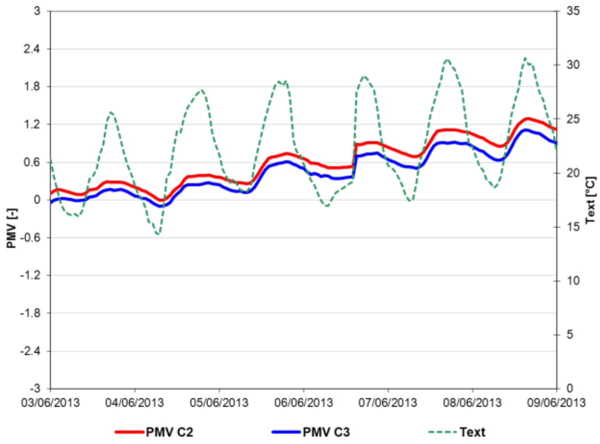

Figure 10: PMV trend - “Comf 1”

Configuration “Comf 2”

In the configuration “Comf C2” it is possible to divide the considered period in two parts. From May 15 to 17, the average external temperature is equal to about 17 °C and the average solar radiation is about 400 W/m^2. In these conditions, no significant changes in thermo-hygrometric comfort between the two cells are recorded. From May 18 to 24, instead, the external temperature and the solar radiation are lower (about 15°C) and higher (about 600 W/m^2), respectively, compared to the previous period. In these conditions, C3 provides the best thermo-hygrometric comfort (Figure 11). The PMV values highlight the differences in the two periods: in the former, the thermo-hygrometric sensation is on the average “neutral”, for both cells, while in the latter the thermo-hygrometric sensation is on the average “slightly cool”, with C3 values higher than C2 and close to “neutral”.

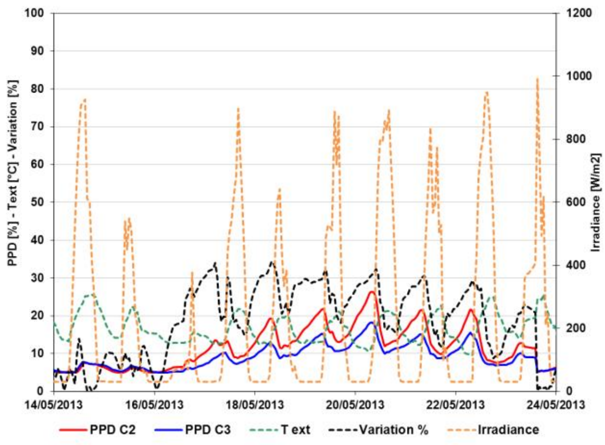

Figure 11: PPD trend - “Comf 2”

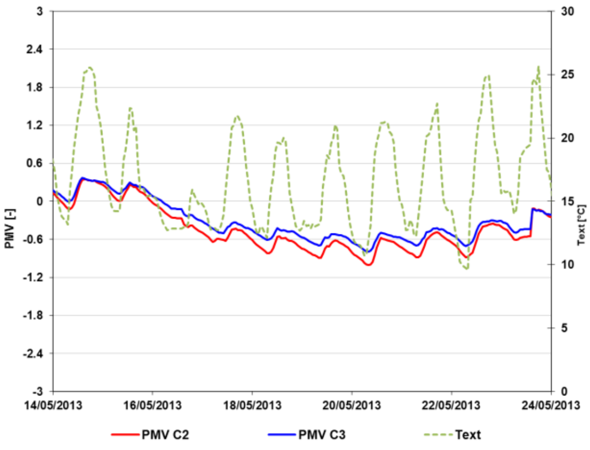

Figure 12: PMV trend - “Comf 2”

6 CONCLUSIONS

This article has investigated the energy behaviour and the comfort level of a dynamic system, consisting of the VetroVentilato® system and a commercial heat recovery unit. The results of the experimentation show that, in winter, the combined system allows for interesting energy savings. When the external temperature is equal to 10 °C, the energy savings that may be achieved with the dynamic system amount to about 38% compared to 8% obtained by the single system alone (without the heat recovery unit) and compared to 20% obtained by the heat recovery unit alone. The analysis shows an improvement of the performances of the combined system. The combined operation of the dynamic system is not the sum of the single contributions; in fact, the system detects higher values due to the pre-heating function of the window.

In summer, the energy savings of the combined system are about 13%, which is lower than the operation of VetroVentilato® alone.

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REFERENCES

Lollini, R., Danza, L., Meroni, I. (2010). Energy efficiency of a dynamic glazing system. Solar Energy, 84(4), 526-537.

Belussi, L., Danza, L. (2012). Method for the prediction of malfunctions of buildings through real energy consumption analysis: Holistic and multidisciplinary approach of Energy Signature. Energy and Building, 55, 715-720..

Stamp, S. (2012) A Summary of the Co-heating test procedure and analysis method, Technical Report.

ANSI/ASHRAE 55:2013. Thermal environmental conditions for human occupancy.

EN ISO 7730:2006. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

EN 15603:2008, For space heating - Overall energy use and definition of energy ratings.

McEvoy M.E., Southall R.G., Baker P.H., Test cell evaluation of supply air windows to characterise their optimum performance and its verification by the use of modelling techniques, Energy and buildings, 35 (2003), pp. 1009-1020.

J.U. Sjogren , S. Andersson, T. Olofsson, Sensitivity of the total heat loss coefficient determined by the energy signature approach to different time periods and gained previous energy, Energy and Buildings, 41 (2009), pp. 801–808.