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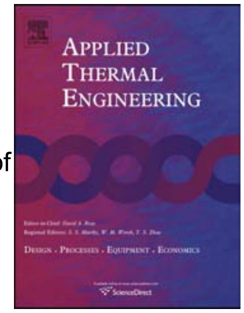

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The effectiveness method to predict the behaviour of a desiccant wheel: an attempt of experimental validation

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Abstract

The desiccant wheel is a key component in solid-desiccant systems. At present, the analysis of the behaviour of air handling units based on desiccant wheels is a complex task. It is difficult to access a simple model that can represent the behaviour of commercialized desiccant wheels with sufficient accuracy.

Experimental data measured in an air handling unit equipped with a desiccant wheel are considered in the present work. The air handling unit belongs to a test facility with a microcogeneration system located at Università degli Studi del Sannio (in Benevento, Southern Italy). Thermal energy from the microcogenerator is used to heat up the regeneration airflow. An attempt of investigating the validity of the simplified effectiveness method in predicting the global behaviour of a desiccant wheel is performed. Two approaches are used with different pair of effectiveness parameters.

Only one sensor of temperature and one sensor of relative humidity were used in each measuring section of the air handling unit. This constraint is most crucial at both outlet

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sections of the desiccant wheel due to the strong dependence of the air state on the angular position.

An empirical correction of the measured state of the process air at the outlet of the desiccant wheel is used. The corrected data are used in the investigation of the validity of the effectiveness method by using constant values in a large set of cases where the rotation speed of the desiccant wheels and the fans are kept constant. Important deviations between the predicted and the experimental results were found in a significant number of cases, therefore there is the need of improving the method by taking into account the effect on the effectiveness parameters of varying the inlet states of both airflows.

Keywords: desiccant wheel, experimental data, effectiveness method, validation, empirical correction

Nomenclature

a_1, b_1, c_1	parameters of Eq. (3)
a_2, b_2, c_2	parameters of Eq. (4)
D_d	diameter of the duct (m)
$F1, F2$	characteristic potentials
h	specific enthalpy (J kg^{-1})
$\dot{m}$	mass airflow rate (kg s^{-1})
p_v	partial pressure of water vapour (Pa)
p_vs	saturation pressure of water vapour (Pa)
RMSD	Root mean square deviation
T	temperature (ºC)

t	time (s)
u	airflow velocity (m s^{-1})
w_{v}	water vapour content of moist air (d.b.) (kg kg^{-1})

Greek symbols

α	correction factor for the outlet state of process air
χ	percentage of cases evidencing unacceptable agreement (%)
δ	maximum deviation between predicted and measured values
η	effectiveness parameter
ρ	air density (kg m^{-3})
σ	ratio of mass airflow rates
ψ	ratio $p_{\mathrm{v}}/p_{\mathrm{vs}}$
τ_{cyc}	sorption cycle duration (s)

Subscripts

F1, F2	parameter related with characteristic potentials
h	parameter related with enthalpy
id	ideal
max	maximum
min	minimum
T	parameter related with temperature
w	parameter related with water vapour content
ψ	parameter related with the ratio $p_{\mathrm{v}}/p_{\mathrm{vs}}$
1	related with process air
1in	inlet of process air

1out	outlet of process air
2	related with regeneration air
2in	inlet of regeneration air
2out	outlet of regeneration air

Superscripts

*	predicted parameter
**	predicted parameter after correction of the outlet state of the process air

Abreviations

Eff-A	approach using (η_{h}, η_{ψ})
Eff-B	approach using (η_{F1}, η_{F2})

1. Introduction

Nowadays the interest in HVAC&R systems based on desiccant wheels is widely increasing due to the possibility of using renewable energy sources with low environmental impact and high potential of fossil fuel consumption and greenhouse gas reduction.

Beccali *et al*. [1] presented instantaneous, daily and monthly energy performance indicators of a Solar Desiccant Evaporative Cooling system, for the cooling operation mode during five months and heating operation mode during three winter months. The system is composed of an air handling unit coupled with a radiant ceiling that provides most of the energy required to remove the sensible cooling/heating load. Flat plate collectors deliver part of the heat required to regenerate the desiccant wheel during the cooling mode and space heating during heating mode. Monthly results are elaborated and seasonal performance indicators such as electric and thermal COP and primary energy savings for cooling and heating operation are presented. Primary energy savings in cooling mode operation, in comparison to a conventional air handling unit, came up to nearly 50%.

Aprile *et al.* [2] investigated the control optimization of a solar assisted air-conditioning concept combining a desiccant and evaporative cooling system with an electrical reversible water/water heat pump. In summer, the heat pump cools the supply air stream and pre-heats the regeneration air when dehumidification is needed; in winter, the heat pump provides auxiliary heat if a minimum temperature is available in the heat storage, otherwise a backup boiler is used. The depicted system has been modelled and an extensive simulation work has been carried out to identify an optimal control strategy. According to the simulation results, the system can deliver primary air at the requested temperature and humidity while holding the overall primary energy consumption at significant low levels compared to reference system solutions, using a gas boiler and an air-condensed chiller.

Primary energy and emissions savings can also be achieved when regeneration of the desiccant wheel is performed by means of thermal wastes from cogeneration systems.

Henning *et al.* [3] showed the results of a simulation model, carried out to design a hybrid desiccant-based HVAC system. A microcogenerator (MCHP, Micro Combined Heat and Power) supplies electric energy to an electric heat pump and other electric devices. Waste heat recovered from the MCHP is used in summer to regenerate the desiccant wheel. Surplus of thermal energy is used to produce domestic hot water. During winter, waste heat is directly used for heating using fan-coils as well as an air handling unit. Regarding energy performance, results indicate an electricity saving greater than 30% in comparison to state-of-the-art solutions based on conventional technology.

Angrisani *et al.* [4] performed laboratory tests to experimentally evaluate a small scale polygeneration system based on a natural gas-fired MCHP and a desiccant-based HVAC system. Cogenerated thermal energy is used for the desiccant wheel regeneration, while electric energy for auxiliaries, chiller and external units. The main results state the increase of the COP of the chiller in desiccant-based HVAC systems. The paper identifies the operating conditions (outdoor and supply air thermal-hygrometric conditions, electric grid efficiency and partial load operation of the MCHP) which guarantee significant primary energy savings (up to around 30%) and CO_2 equivalent emission reductions (up to around 40%) of the polygeneration system compared to a conventional HVAC system.

However, the dynamic energy analysis of air handling units based on desiccant wheels remains difficult. The use of simple methods to describe the global behaviour of a desiccant wheel, such as the effectiveness method, is an interesting approach, but it requires the previous knowledge of the dependence of the effectiveness parameters on the operating conditions.

Several test facilities integrating a desiccant wheel are operated in Germany [5], Italy [1-4;6-12] and Turkey [13]. Some attempts regarding the validation of simulation models of desiccant wheels have been done by comparing experimental data with the predicted results. This kind of studies is not easy to be carried out with high accuracy in real systems, mainly due to the difficulties in measuring each outlet state of the airflow exiting the desiccant wheel with only one sensor of temperature and one sensor of humidity. Moreover, very few works indicate mass and energy imbalance errors or the whole set of data that would enable their calculation. The exhaustive experimental research in lab conditions [14] showed significant mass and energy imbalances between the regeneration and the process air streams crossing a desiccant wheel.

In most experimental researches the process airflow rate, the inlet state of process air, the inlet state of regeneration air and the outlet state of process air are measured only in one point of each air stream.

Several experimental and numerical research works have addressed the performance analysis of desiccant wheels, however studies specifically focusing on the characterization of the effectiveness parameters are scarce. Some works based on simulations of systems integrating a desiccant wheel adopt different definitions of effectiveness parameters. In most of them, the approach of Maclaine-Cross and Banks, commonly known as the analogy theory, has been adopted taking into account two independent potential variables $F1$ and $F2$.

Additional research is still needed, particularly to determine the most useful effectiveness parameters and the respective correlations that might be suitable for sizing purposes, as well as to perform dynamic energy simulations of HVAC&R systems integrating desiccant wheels. The objective of the present work is to investigate the viability of using the effectiveness method for the prediction of the global behaviour of a desiccant wheel. The study is based on the analysis of the experimental data measured in an air handling unit. Two pairs of the effectiveness parameters are tested, together with and without an attempt of correction of the measured outlet state of the process airflow.

2. Effectiveness parameters

In the classical analysis of the thermal behaviour of heat exchangers, the concept of effectiveness results from the comparison between the behaviour of a real heat exchanger with that of an ideal one, adopted as a reference. Due to the coupled processes of heat and mass transfer, the application of the effectiveness method to a desiccant wheel requires the use of two independent effectiveness parameters. Furthermore, those parameters should be quite independent of the inlet states of both airflows or, at least, easily correlated with them.

The ideal and the real curves representing the outlet states and the psychrometric evolutions in both airflows are represented in Fig. 1, for equal inlet mass airflow rates and water vapour contents in the process air (airflow 1) and in the regeneration air (airflow 2). An example of possible real evolutions (1in→1out and 2in→2out) is schematically represented in Fig. 1. Varying only the rotation speed (i.e., the sorption cycle duration τ_{cyc}), the ideal outlet states of both airflows lie on the dashed line curves, while the real outlet states correspond to the solid line curves. The ideal behaviour of a desiccant wheel is represented by the ideal evolutions 1in→1out,id and 2in→2out,id.

The deviation of the curves representing the real outlet states of both airflows relatively to the ideal ones, as illustrated in Fig. 1, is an indicator of the effectiveness of the heat and mass transfer phenomena.

The approaches of the effectiveness method here investigated are supported by the use of the pairs ($\eta_{\mathrm{h}}, \eta_{\psi}$) and ($\eta_{\mathrm{F1}}, \eta_{\mathrm{F2}}$) and are named Eff-A and Eff-B, respectively. In the first approach, the effectiveness parameters are based on the changes of specific enthalpy h:

$$\eta_{\mathrm{h}} = \frac{h_{\mathrm{1in}} - h_{\mathrm{1out}}}{h_{\mathrm{1in}} - h_{\mathrm{2in}}} \tag{1}$$

and on the changes of the variable ψ:

$$\eta_{\psi} = \frac{\psi_{\mathrm{1in}} - \psi_{\mathrm{1out}}}{\psi_{\mathrm{1in}} - \psi_{\mathrm{2in}}} \tag{2}$$

The equilibrium relation of several desiccants is usually expressed with a good accuracy by a relationship between the adsorbed water content and $\psi = p_\mathrm{v}/p_\mathrm{vs}$. It is important to stress that the variable ψ corresponds to the relative humidity of the air in those states where the definition of the relative humidity is applicable, *i.e.*, when the air temperature is lower than the water saturation temperature at local atmospheric pressure.

To the best of the authors' knowledge, the pairs of effectiveness parameters $(\eta_\mathrm{h}, \eta_\psi)$ have been investigated only in few recent works [15-18].

The maximum moisture removal capacity of a desiccant wheel occurs at the particular condition that minimizes the water vapour content of the outlet process airflow, a state of the air that is represented by the point 1out,op in Fig. 1.

The pair of effectiveness parameters that has been commonly used since long time is based on the characteristic potentials $F1$ and $F2$, which can be seen as psychrometric variables: the $F1$ lines are close to the moist air specific enthalpy lines and the $F2$ lines are close to those of the ratio $\psi = p_\mathrm{v}/p_\mathrm{vs}$. The dependence of these characteristic potentials on temperature and water vapour content was investigated by Jurinak [19] for active silica-gel desiccant wheels and the following mathematical functions were proposed:

$$F1 = \frac{1}{a_1}\left(\frac{T + 273.15}{273.15}\right)^{a_1} + \mathrm{b}_1 \frac{w_\mathrm{v}^{c_1}}{c_1} \qquad (3)$$

and

$$F2 = \frac{1}{a_2}\left(\frac{T + 273.15}{273.15}\right)^{a_2} + \mathrm{b}_2 \frac{w_\mathrm{v}^{c_2}}{c_2} \qquad (4)$$

with T and w_v expressed, respectively, in ºC and $\mathrm{kg\,kg^{-1}}$. The values of the coefficients and exponents of both equations are listed in Table 1.

In the second approach, Eff-B, the effectiveness parameters based on the changes of the characteristic potentials are defined as:

$$\eta_{F1} = \frac{F1_{1in} - F1_{1out}}{F1_{1in} - F1_{2in}} \quad (5)$$

and

$$\eta_{F2} = \frac{F2_{1in} - F2_{1out}}{F2_{1in} - F2_{2in}} \quad (6)$$

The ideal outlet states of both airflows, considered as reference states, are here assumed to be dependent only on the inlet conditions of both airflows, and independent of other parameters, such as: airflow rates, rotation speed, dimensions of the wheel and of the channels of the hygroscopic matrix, and ratio of process to regeneration areas.

Other pairs of effectiveness parameters based on the changes of the temperature (temperature efficiency) and on the water vapour content (dehumidification efficiency) are referred in literature [15], but their use in application of the effectiveness method has been scarce. Nevertheless, these parameters should also be investigated in a more extensive work.

3. Experimental setup

The experimental data used in the present work was measured in an air handling unit that belongs to the test facility depicted in Fig. 2. The system is located at "Università degli Studi del Sannio" (in Benevento, Southern Italy) and was experimentally analysed in previous research works [7-12]. The type, measuring range and accuracy of installed sensors, as well as the legend for the symbols, are also shown in Fig. 2.

The regeneration of the desiccant matrix of the wheel is performed at low temperature, ranging from 60 to 70 ºC. The thermal energy used to heat the regeneration airflow is recovered from a MCHP and/or supplied, if necessary, by a natural gas-fired boiler.

The experimental setup presents several differences relatively to the common desiccant-based air handling units. It uses three airflows: process air, regeneration air and cooling air. It also uses a heat exchanger and an evaporative cooler, but in this case the heat exchanger performs the heat transfer from the process air to the cooling air and the evaporative cooler is used to cool the cooling air. With this arrangement of components, the regeneration airflow is not humidified before it enters the regeneration section of the desiccant wheel, hence avoiding reduction of its dehumidification capacity.

The air handling unit is not intended to carry out experimental tests at steady state conditions. The inlet states of the process and regeneration airflows are dependent on the atmospheric conditions. Moreover, due to practical constraints the airflow is not well mixed and it is also not well stabilized at measuring sections. These aspects lead to difficulties in measuring with high accuracy the different operating parameters.

Furthermore, each airflow that enters the unit should be previously controlled in a specific chamber or in a specific air handling unit to guarantee the control of the inlet conditions enabling the testing of the desiccant wheel at particular steady operating conditions. This strategy would enable testing the recent simplified procedure of using the effectiveness method [16-18].

Only one sensor of temperature and one sensor of relative humidity were used in each measuring section. This constraint is most crucial at both outlet sections of the desiccant wheel due to strong dependence of the air state on the angular position. Being recognized that in those sections the airflow is not well mixed, the use of more sensors at each section should be adopted. Nevertheless, it seems important to use the large set of experimental data of this system to investigate the behaviour of the different components, taking into account the well-known constraints that also exist in common manufactured air handling units.

The changes observed on the temperature and water vapour content of each airflow during each test can be used to inspect the unbalance on energy and mass between both airflows. Assuming that the air passages between both sectors of the desiccant wheel and that leakages are negligible, the mass and energy balances can be used to evaluate the ratio between both mass dry airflows rates $\sigma = \dot{m}_2 / \dot{m}_1$. This ratio can be evaluated by:

$$\sigma_{\mathrm{T}} = \frac{T_{1\mathrm{out}} - T_{1\mathrm{in}}}{T_{2\mathrm{in}} - T_{2\mathrm{out}}} \tag{7}$$

or by:

$$\sigma_{\mathrm{w}} = \frac{w_{\mathrm{v,1in}} - w_{\mathrm{v,1out}}}{w_{\mathrm{v,2out}} - w_{\mathrm{v,2in}}} \tag{8}$$

Experimental data were measured during a period of three years to investigate how the inlet states and airflow rates of both airflows and the rotation speed of the desiccant wheel influence the overall behaviour of the desiccant wheel. In the present paper only the results of the large set of tests carried out during the year 2009 are considered to investigate the validity of using the effectiveness method supported with constant values when the inlet states vary and the rotation speed of the desiccant wheel and the fans are kept constant.

In each test, the set-point values of rotation speed of the fans, regeneration air temperature and rotation speed of the wheel were fixed during a period of 20 minutes approximately and the inlet and outlet states of both airflows as well as both velocities were measured with a frequency of 1 Hz.

The atmospheric pressure considered in the calculations is assumed to be equal to 101325 Pa since the experimental setup is located at approximately sea level height.

Both process and regeneration airflow velocities were measured inside a duct with an internal diameter of D_d=0.240 m. The measured values of the air velocity u enables the estimation of the mass airflow by the relationship $\dot{m} = 0.25 \rho u \pi D_d{}^2$, in which the air density is estimated with the measured temperature, the measured relative humidity and the assumed atmospheric pressure value. To have an accurate estimation of the velocity, and hence of the mass flow rate, with only one velocity sensor, it has been installed in the air duct as specified by the manual in order to obtain turbulent flow conditions at the measuring point: the sensor is placed far from dampers and duct direction changes, and with straight sections, upstream and downstream of the sensor, equal to 6 and 3 times the diameter of the duct, respectively.

The air states in both measurement points are equal because both process and regeneration airflows are outside air. So, the inlet water vapour content of the regeneration airflow entering the desiccant wheel is equal to the value calculated for the inlet process airflow with the measured values of temperature and relative humidity.

Fig. 3 depicts the results obtained during a particular test. Fig. 4 summarizes the measured data for the whole set of 89 tests in which the rotation speed of the desiccant wheel was fixed at 12 rph. It is observed that both air velocities are not constant as ideally would be desirable. The inlet temperature of the process air ranged from 22.2 to 38.8 ºC and the inlet temperature of the regeneration air ranged from 49.8 to 68.6 ºC. Both inlet water vapour contents varied between 6.4 and 15.9 g kg^{-1}.

A ratio of the average mass airflows rates $\sigma = \dot{m}_2 / \dot{m}_1$=1.093 is estimated by using the measured inlet velocities values. The ratios σ_T and σ_w determined by the energy and mass balances are shown in Fig. 5.

Important deviations exist between the average value $\sigma = 1.093$ and the values of the ratios σ_T and σ_W in a significant number of tests. Probably, those observed significant deviations are an indicator that the measured outlet states of both airflows at the desiccant wheel in a particular point do not represent well the mixed condition assumed when using Eqs. (7) and (8). Moreover, due to the agreement found between parameters derived from the experimental measured data and results published [7, 10-12], it is quite probable that the most important deviations are due to errors on measuring the outlet state of the regeneration airflow.

In most of published research works dealing with experimental results of the overall behaviour of a desiccant wheel, it is impossible to inspect on the unbalance errors because those works present the measured values for both inlet states and for the outlet state of the process airflow only. Very few published experimental works indicate the measured states of the outlet states of both regeneration and process airflows.

The achieved deviations between estimated ratios σ_T and σ_W and the ratio σ evidence the difficulties on performing the energetic analysis of an existing particular installation integrating a desiccant wheel. Another additional difficulty is the quantification of the mass airflow passages from the process side to the regeneration side or vice versa. Very few experimental works provide measurements of the airflow rates at the inlet and outlet of the wheel to access on the quantification of the mass airflow rate passage.

In spite of the important magnitude of the registered unbalance errors, the present paper attempts to investigate the dependences of two pairs of effectiveness parameters on the inlet states of both process and regeneration airflows. It is important to notice that the probable high errors in measuring the outlet state of the regeneration air do not influence both pairs of effectiveness parameters here analysed.

The measured value of the different variables was averaged for a period of 1 minute, but only the average value of the last 5 minutes period of each test is considered here to be representative of the steady state behaviour of the desiccant wheel.

The two pairs of effectiveness parameters, (η_{h}, η_{ψ}) and (η_{F1}, η_{F2}), predicted for each test are presented in Fig. 6.

A significant number of research studies has been performed assuming negligible dependence of the pair of effectiveness parameters on the inlet states when applying the effectiveness method. In most of those studies the approach Eff-B supported by the pair (η_{F1}, η_{F2}) has been used. The dispersion of points represented in Fig. 6 seems to indicate that such assumption is questionable. As an exercise of assessment on the validity of the use of the effectiveness method by constant values, the outlet states are now predicted by the effectiveness method considering constant effectiveness values equal to the average values of the 89 tests. The following average values are found: η_{h}=0.225; η_{ψ}=0.931 and η_{F1}=0.211; η_{F2}=0.753.

Fig. 7 depicts the measured state ($T_{1out}, w_{v,1out}$) and state ($T^{*}_{1out}, w^{*}_{v,1out}$) predicted by the effectiveness method using both approaches Eff-A (η_{h}=0.225, η_{ψ}=0.931) and Eff-B (η_{F1}=0.211, η_{F2}=0.753). It is observed that both approaches Eff-A and Eff-B predict the outlet state of the process air with similar deviations relatively to the measured data. The RMSD values and the maximum deviations $\delta_{Tmax} = \max\left|T_{1out} - T^{*}_{1out}\right|$ and $\delta_{wmax} = \max\left|w_{v,1out} - w^{*}_{v,1out}\right|$ are indicated in Table 2. The analysis of the achieved RMSD values indicates that both approaches predict results with acceptable accuracy.

In the authors´ point of view it is also important to investigate the errors in evaluating, in a dimensionless way, the mass and heat transfer rates defined by

$\delta_{\mathrm{T}}^{+} = \left(T_{1\mathrm{out}} - T_{1\mathrm{out}}^{*}\right) \big/ \Delta T_{\mathrm{ref}}$ and $\delta_{\mathrm{w}}^{+} = \left(w_{\mathrm{v,1out}} - w_{\mathrm{v,1out}}^{*}\right) \big/ \Delta w_{\mathrm{v,ref}}$, respectively. The reference here adopted values for the increase in temperature and decrease in water vapour content of the process air are $\Delta T_{\mathrm{ref}} = 50$ ºC and $\Delta w_{\mathrm{v,ref}} = 15$ g kg^{-1}. The errors on the mass (δ_{w}^{+}) and heat (δ_{T}^{+}) transfer rates corresponding to the obtained RMSD values are of about 5 % and 3 %, respectively. When considering the values of δ_{Tmax} and δ_{wmax}, the errors δ_{w}^{+} and δ_{T}^{+} become about 17% and 9%, respectively.

It is also important to investigate the percentage of cases where the deviation on those transfer rates is greater than the minimum acceptable value that in the present work is fixed in 5%. The achieved percentages, denominated by χ_{T} and χ_{w}, are indicated also in Table 2. In both approaches Eff-A and Eff-B the achieved percentage values are not negligible.

It is important to notice that in a previous paper [7], using measured data at the same experimental setup and in the same year of 2009, it was concluded that the agreement between measured and predicted values, by the effectiveness approach Eff-B, is quite good. Only few values were outside of the represented ±5% error band relatively to the variable $w_{\mathrm{v,1out}}$. In that study a set of 41 selected cases was considered instead of the set of 89 cases in the present investigation. The obtained RMSD values were of 1.28 ºC and 0.301 g kg^{-1}, respectively for $T_{1\mathrm{out}}$ and for $w_{\mathrm{v,1out}}$. The maximum deviations were δ_{Tmax}=2.96 ºC and δ_{wmax}=0.896 g kg^{-1}. For that reason, a maximum deviation of about 6% was registered in both the mass and heat transfer rates. The deviations of both mass and heat transfer rates are higher than 5% just in one case ($\chi_{\mathrm{T}} = \chi_{\mathrm{w}}$ =2.4%). This assessment supported the conclusions regarding the validity of the effectiveness method using constant values [9], not corroborating the assessment in the present investigation using a set of cases much more complete.

Without the chance to repeat the experiments with more accuracy, the following correction of the outlet state of process air is investigated:

$$w^{**}_{v,1out} = w_{v,1out} + \alpha_w \left(w_{v,1in} - w_{v,1out,id} \right) \quad (9)$$

$$T^{**}_{1out} = T_{1out} + \alpha_T \left(T_{2in} - T_{1in} \right) \quad (10)$$

In order to improve the accuracy of the results for the whole set of cases several correction tests were performed by testing different values of the corrections factors α_T and α_w. The minimum achieved values of parameters χ_T and χ_w determined in this assessment were achieved when the correction of the outlet states are $\alpha_T = -0.025$ and $\alpha_w = 0.05$. The Fig. 8 shows the corresponding results. The maximum deviations between the measured values and the corrected values are 1.05 ºC and 0.417 g kg^{-1} for T_{1out} and for $w_{v,1out}$, respectively. New pairs of averaged values (η_h=0.224, η_ψ=0.906) and (η_{F1}=0.215; η_{F2}=0.708) were determined by using the data of Fig. 8. The effectiveness method was applied again twice. The percentages of cases evidencing unacceptable agreement between predicted and measured values are less, but remain significant in both approaches Eff-A and Eff-B. In case of approach Eff-A it was registered χ_T =11.2 % and χ_w =22.5 % and in case of approach Eff-B χ_T =11.2 % and χ_w =27.0 %.

This assessment can be seen as an indicator for the need of improving the application of effectiveness method by taking into account a recent investigated procedure [16, 18] to include the effect of varying the inlet states of both airflows. The fact that both airflow rates do not remain strictly constant in all performed tests of set A (see Fig. 4a)) also has some effect on the relative high values of the percentages χ_T and χ_w. The results predicted by approaches Eff-A and Eff-B lead to the conclusion that the accuracy of the results of both is similar. However, approach Eff-A is more advantageous because it is supported by well-known psychrometric variables independently of the used desiccant and the prediction of the outlet states of the process air for given values of the effectiveness parameters is easier. When using approach Eff-B, the calculation of the outlet state of the process air from the variables $F1$ and $F2$ for given values of the effectiveness parameters is not so simple.

Being recognized that in those sections of a real system the airflow is not well mixed at both outlet of the desiccant wheel, the use of more sensors at each section should be adopted following for example the procedure suggested by Aprile and Motta [6].

4. Conclusions

This paper reports an investigation conducted on the imbalance between process and regeneration airflows of a desiccant wheel, as well as about the validity of the simplified effectiveness method in predicting the global behaviour of a desiccant wheel.

Experimental data, measured in an air handling unit equipped with a desiccant wheel, located at Università degli Studi del Sannio, in the South of Italy, were used.

First of all, the measured values of mass flow rates, as well as the inlet and outlet thermo-hygrometric properties of both process and regeneration air were used to evaluate the ratio between mass dry airflows rates σ, in terms of both temperature (σ_T) and water vapour content (σ_w). Important deviations were found between the σ_T and σ_w values and the average value $\sigma = 1.093$ for a significant number of tests, with σ_T ranging from 0.56 to 1.55, and σ_w ranging from 0.31 to 1.17. The most important deviations are probably due to errors on measuring thermo-hygrometric properties at regeneration outlet section, as some parameters, derived from the same test facility for the process air flow, agree with values and trends found in the literature.

A further reason of deviations between energy and mass balances is that at the measuring sections the airflows are not well mixed, therefore the use of more sensors at each section should be adopted.

Nevertheless, the experimental data were then used to evaluate both pairs of the effectiveness parameters (η_{F1}, η_{F2}) and (η_h, η_ψ), to test the effectiveness method with constant values.

The result is that the points are quite dispersed: η_h ranges from 0.05 to 0.41, η_ψ from 0.75 to 1.1, η_{F1} from 0 to 0.42, η_{F2} from 0.55 to 1.1. This indicates that the assumption of a constant value of the effectiveness parameters in the analyzed range of operating conditions is not applicable, and a dependence of the pair of effectiveness parameters on the inlet states should be introduced.

To further confirm the low validity of the use of the effectiveness method by constant values, the outlet states were predicted by the effectiveness method considering constant values – equal to the average values of the tests – for both pairs of the effectiveness parameters. Both approaches predict the outlet state of the process air with similar deviations, and with quite high values of RMSD and maximum deviations on both temperature and water vapour content values.

Furthermore, the percentage of cases where the deviations on the mass and heat transfer rates are greater than the minimum acceptable value (5%) is not negligible in both approaches, the lowest value being 11.2% and the greatest being 30.0%.

Consequently, an empirical correction of the measured state of the process air at the outlet of the desiccant wheel was investigated, and new pairs of averaged values of effectiveness parameters were calculated, to apply the effectiveness method again. The percentage of cases evidencing unacceptable agreement between predicted and measured values still remains significant in both approaches, based on (η_{F1}, η_{F2}) and (η_h, η_ψ). This determines the need of improving the application of the method by taking into account the effect on the effectiveness parameters of varying the inlet states of both airflows.

This assessment contradicts the conclusions mentioned in the research works using experimental data [7,15] related to the fact that the effectiveness parameters do not change significantly when the investigated desiccant wheels operate at constant rotation speed and constant airflow rates. However, two recent works [16,18] demonstrated that the effectiveness method supported by constant effectiveness values provides results with unacceptable accuracy in a significant number of cases. The contradictory conclusions can probably be justified by the reduced number of experiments used in studies [7,15]. So, the application of the constant effectiveness method in some published studies, e.g. [20], is questionable.

The differences between the results predicted by both approaches allow to state that the accuracy of both is similar. However, the approach based on (η_h, η_ψ) is more advantageous, because it uses well-known psychrometric variables, not dependent on the used desiccant, and because it is easier to predict the outlet states of the process air for given values of the effectiveness parameters.

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Figure captions

Fig. 1. Schematic representation of real and ideal psychrometric evolutions in a desiccant wheel.

Fig. 2. Experimental setup.

Fig. 3. Results of a particular test: a) airflow velocity, b) airflow temperature and c) airflow water vapour content.

Fig. 4. Results of the whole set of tests: a) mass airflow rate, b) inlet states and c) outlet states

Fig. 5. Ratios σ_T and σ_w estimated for the whole set of tests

Fig. 6. Effectiveness parameters of set of tests A: a) (η_h, η_ψ) and b) (η_{F1}, η_{F2}).

Fig. 7. Outlet states of the process air: a) temperature and b) water vapour content.

Fig. 8. Effectiveness parameters of tests A considering $\alpha_T = -0.025$ and $\alpha_w = 0.05$: a) Eff-A and b) Eff-B.

Table 1 – Values of coefficients and exponents used in Eqs. (3) and (4).

a_1	-1.4899998	a_2	1.4899998
b_1	3.7463964	b_2	-0.0898325
c_1	0.8624176	c_2	0.0796875

Table 2 – Comparative analysis of the results of both approaches Eff-A and Eff-B.

	Eff-A	Eff-B
RMSD T_{1out} (ºC)	1.46	1.50
RMSD $w_{v,1out}$ (g kg^{-1})	0.81	0.89
δ_{Tmax} (ºC)	4.46	5.00
δ_{wmax} (g kg^{-1})	2.49	2.75
χ_T (%)	12.4	11.2
χ_w (%)	23.6	30.0

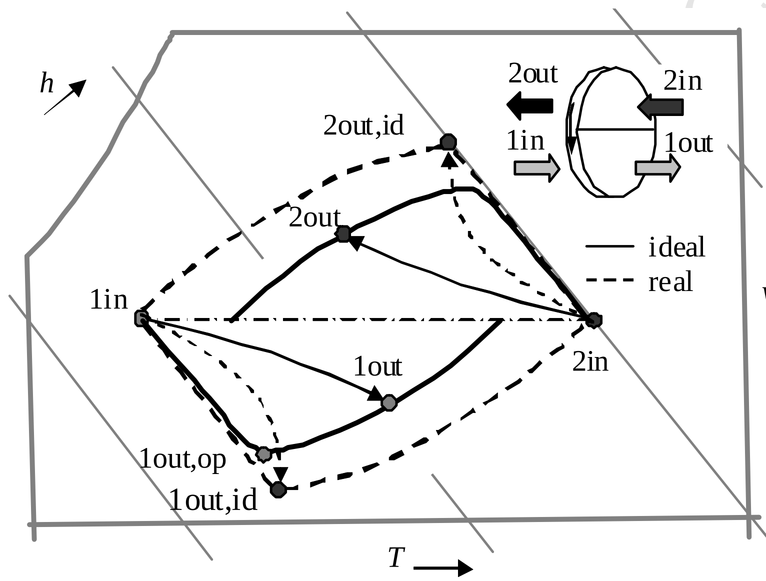
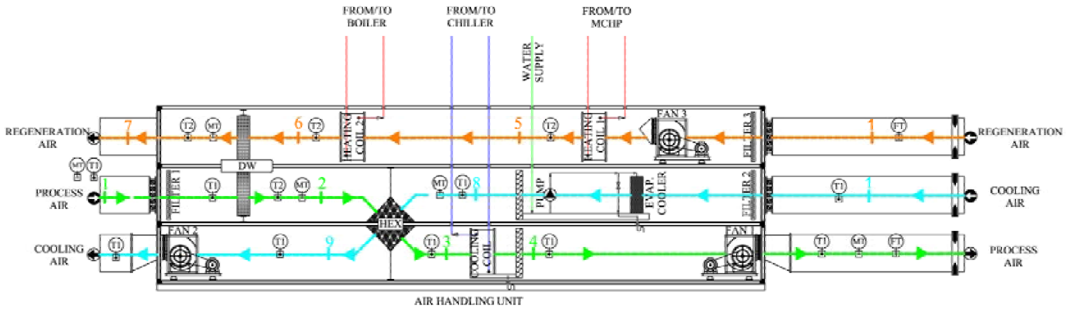

h
2out,id
2out
2in
1in
1out
ideal
real
wv
1in
2out
2in
1out
1out,op
1out,id
T

Fig. 1



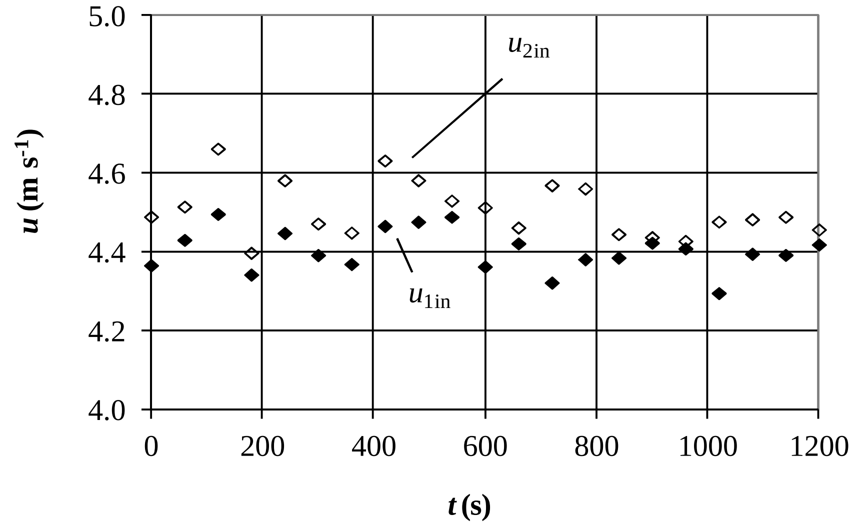
SENSORS

SYMBOL	MEASURED PARAMETER	MEASURING RANGE	ACCURACY	TYPE
T1	AIR TEMPERATURE	-50 / +50 °C	± 0.5 °C	Pt-100
T2	AIR TEMPERATURE	-10 / +90 °C	± 0.15 °C	Pt-100
MT	AMBIENT RELATIVE HUMIDITY	0 - 99%	± 2% RH (5-90% RH) ± 2.5% RH (0-5% and 90-100% RH)	capacitive hygrometer
FT	AIR VELOCITY	0 - 10 m/s	± 0.2 m/s + 3% of measured value	immersion stem

LEGEND

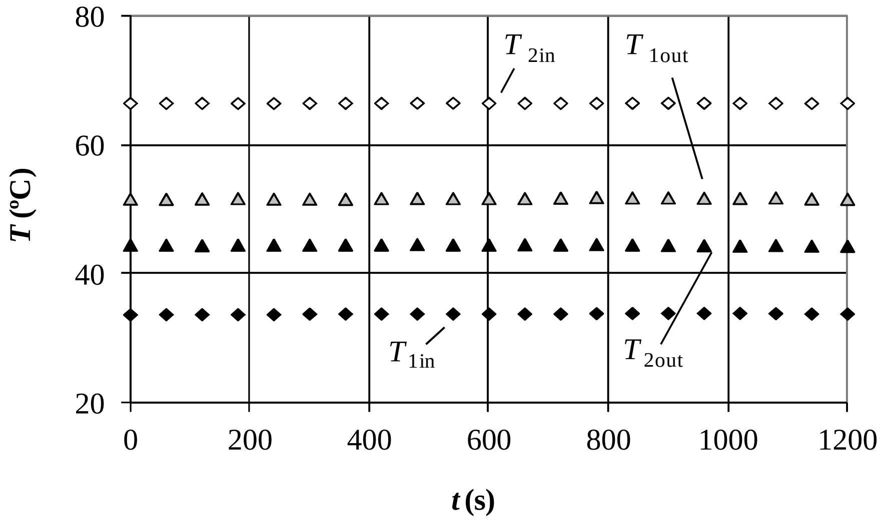
	GATE VALVE
	BALANCE VALVE
	FILTER
	THREE-WAY VALVE
	PUMP

Fig. 2



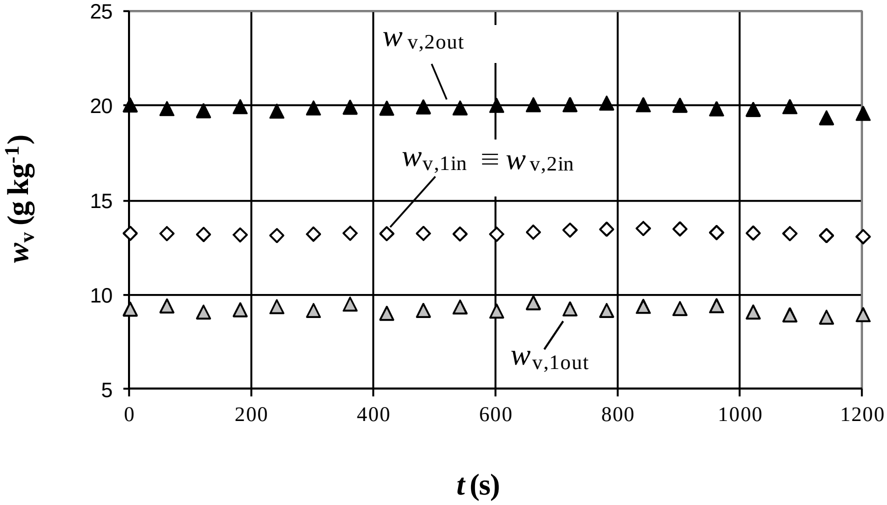
a)

Fig. 3


80
60
40
20
T (ºC)
0
200
400
600
800
1000
1200
t (s)
T 2in
T 1out
T 1in
T 2out

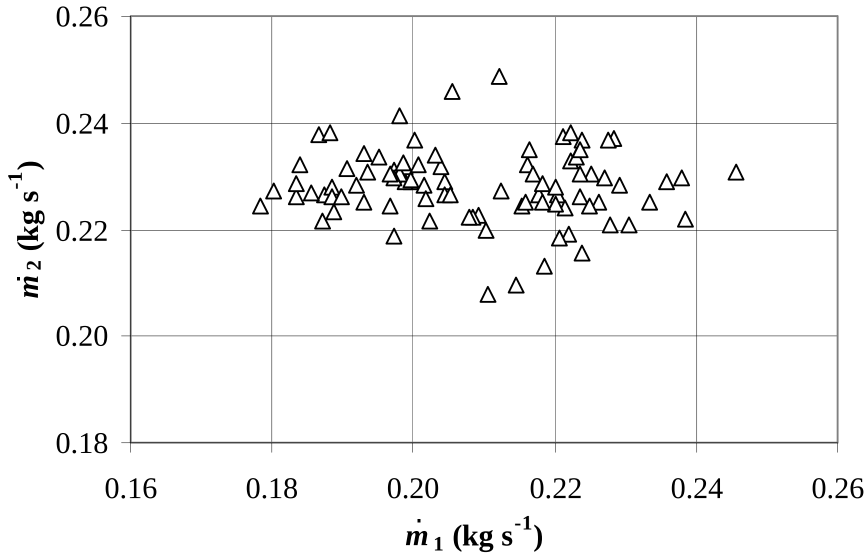
b)

Fig. 3 (cont.)


25
20
15
10
5
0
200
400
600
800
1000
1200
w v,2out
wv,1in ≡ w v,2in
wv,1out
wv (g kg-1)
t (s)

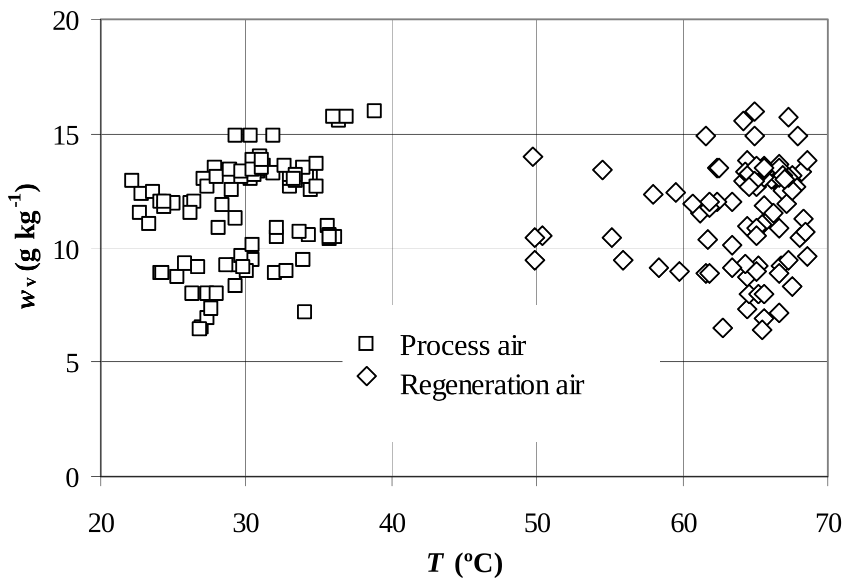
c)

Fig. 3 (cont.)


0.26
0.24
0.22
0.20
0.18
$\dot{m}_2$ (kg s^{-1})
0.16
0.18
0.20
0.22
0.24
0.26
$\dot{m}_1$ (kg s^{-1})

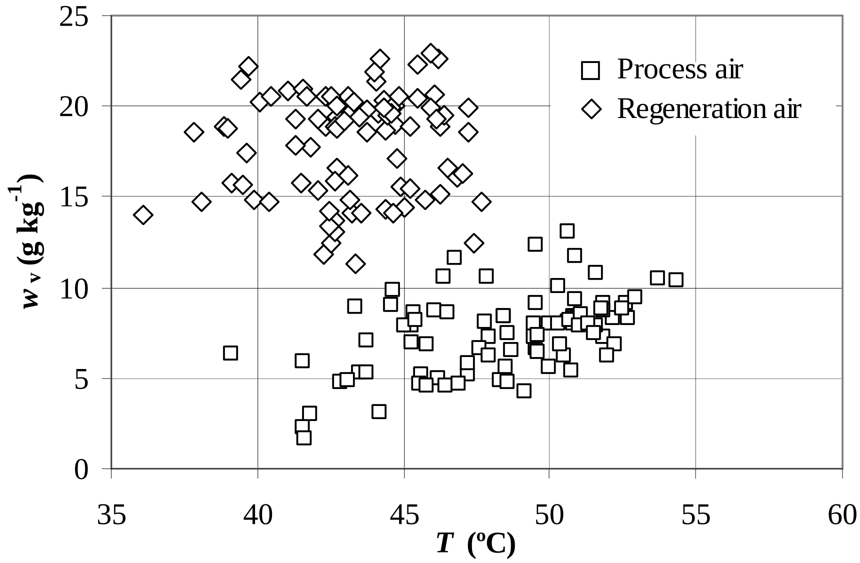
a)

Fig. 4


20
15
10
5
0
w_v (g kg^{-1})
20
30
40
50
60
70
T (ºC)
Process air
Regeneration air

b)

Fig. 4 (cont.)



25
20
15
10
5
0
35
40
45
50
55
60
w_v (g kg^{-1})
T (ºC)
Process air
Regeneration air

c)

Fig. 4 (cont.)

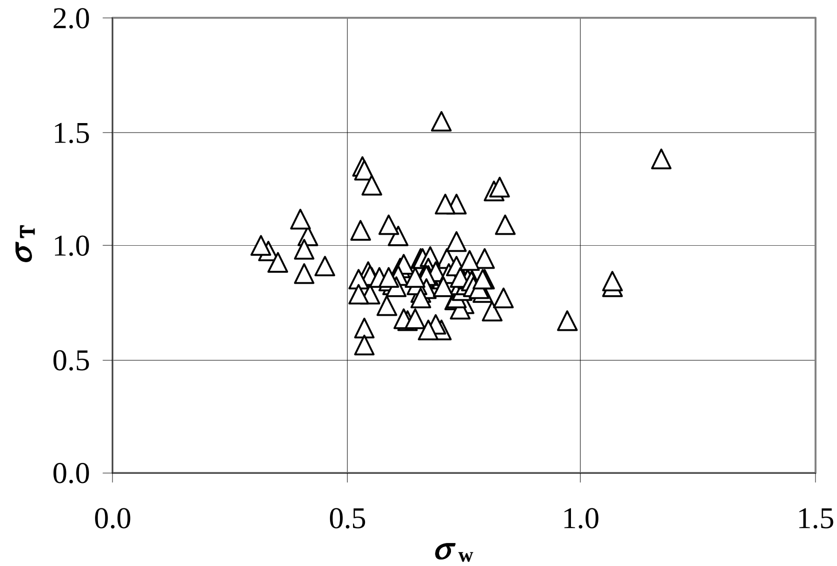
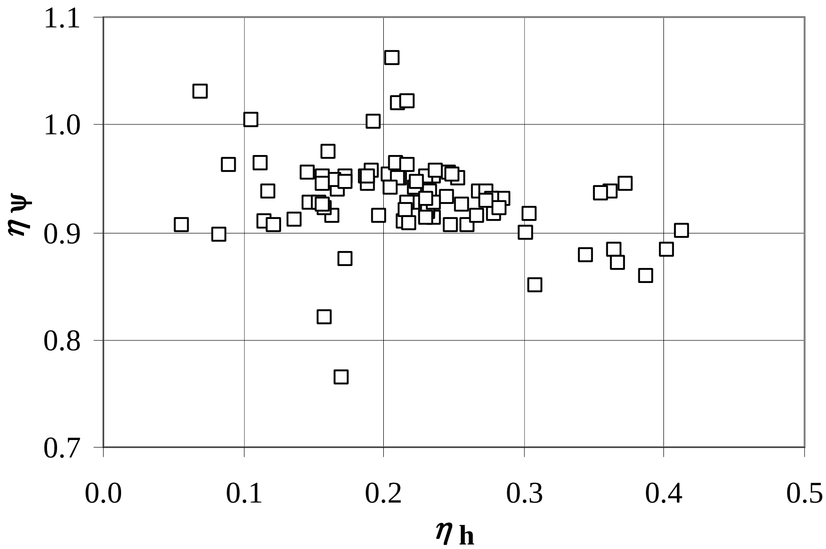
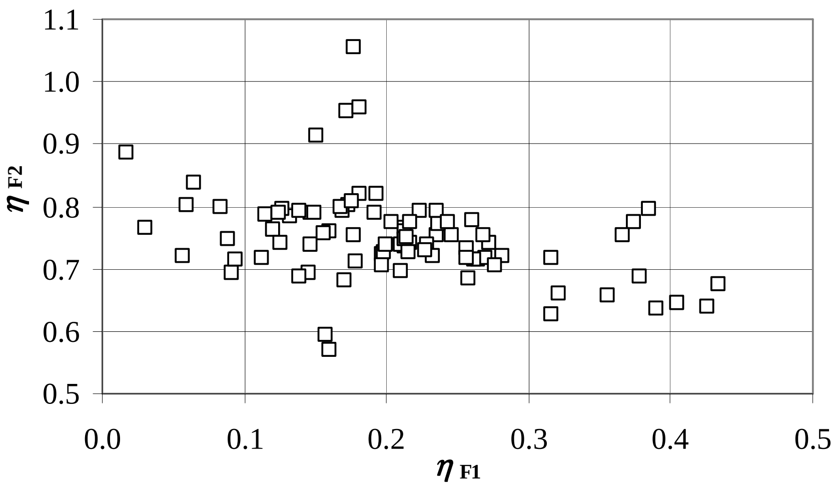


Fig. 5



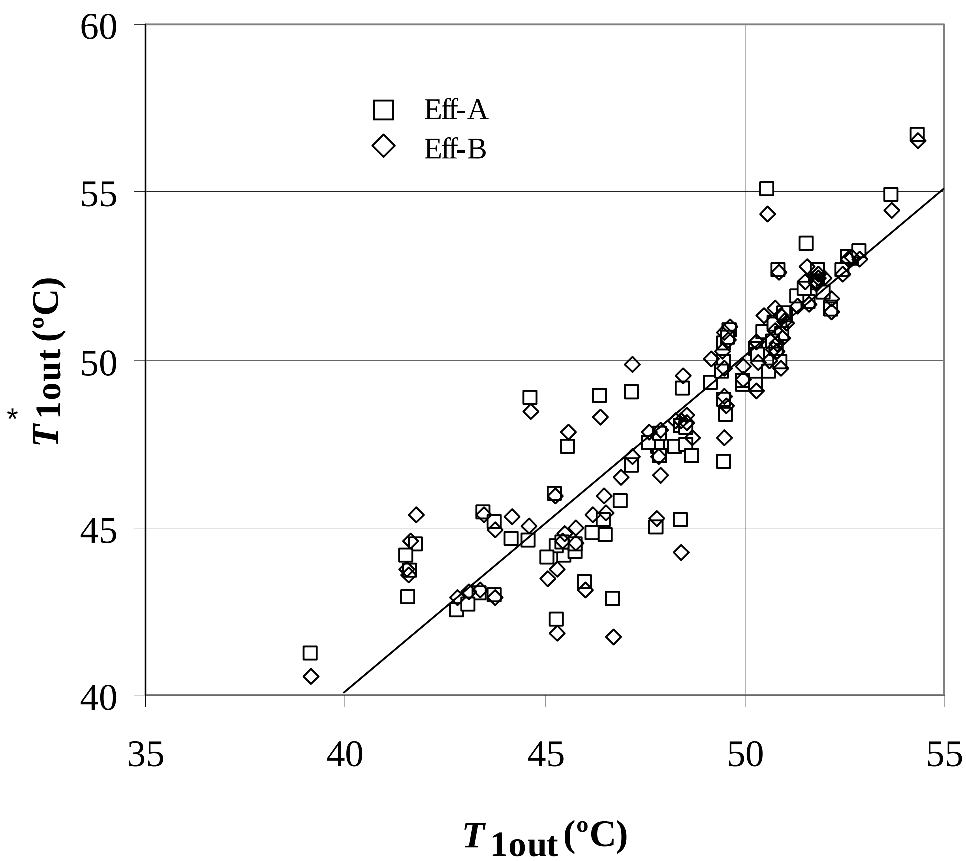
a)

Fig. 6



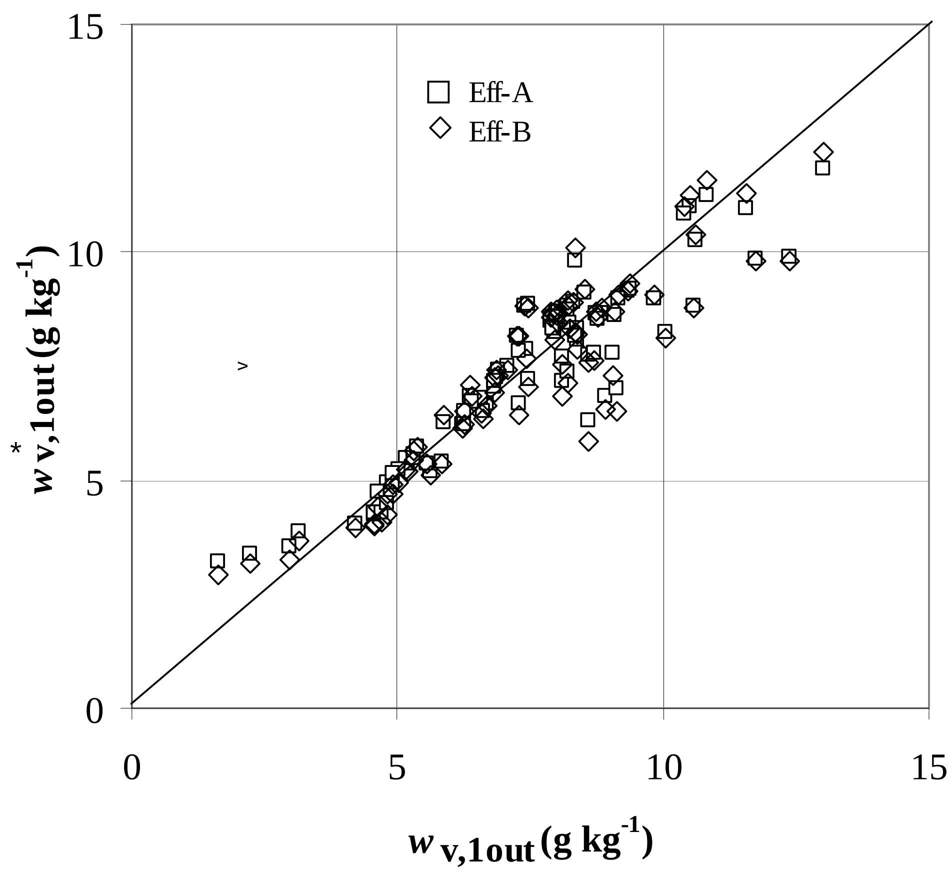
b)

Fig. 6 (cont.)



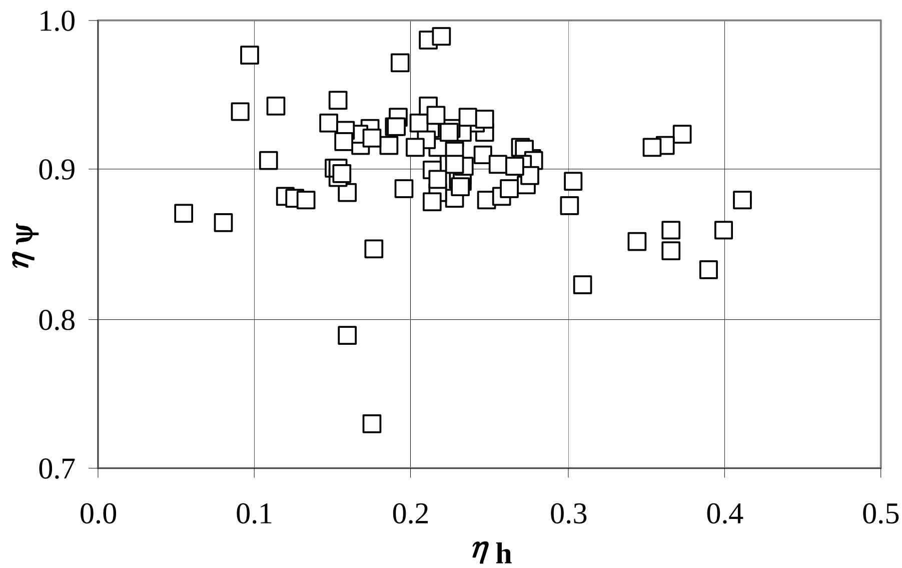
a)

Fig. 7



b)

Fig. 7 (cont.)



a)

Fig. 8

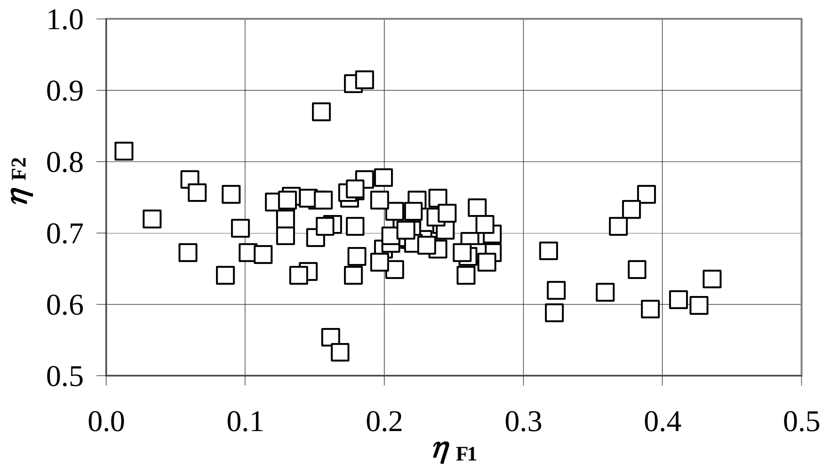


Fig. 8 (cont.)

- The overall behaviour of a desiccant wheel is investigated
- Two pairs of effectiveness parameters are considered
- The study is supported by experimental data measured in an air handling unit
- An attempt of validation of the effectiveness method is performed
- A correction of the measured outlet state of the process airflow is required