Adsorbent materials for low-grade waste heat recovery: application to industrial pasta drying processes

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Abstract

Energy intensive industries face strong challenges due to rising electricity costs and environmental limitations, therefore, developing methods for energy efficiency improvement is becoming an increasingly important issue. With an estimated 30% of industrial energy input being lost as waste heat, its recovery represents an interesting energy efficiency solution potentially providing for a zero-emission, low cost and abundant resource.

This study presents an innovative technology for low-grade waste heat recovery based on advanced adsorbent materials, specifically applied to the drying process of alimentary pasta. Warm and humid air flow resulting from the drying process represents a high-enthalpy waste heat source that, if recovered, can significantly improve the process efficiency. This can be achieved by means of high specific surface materials among which Metal Organic Framework (MOF) compounds represent a promising solution.

In this work, the industrial pasta production process has been studied and possible plant design options identified, including an innovative adsorption cycle to recover waste heat from the drying process. The thermodynamic processes involved in pasta drying plants have been quantitatively analysed to assess the energy savings that can be achieved by using adsorbent materials such as MOFs. Results point to thermal energy savings in the range 40–50%.

Keywords: Metal Organic Framework, energy savings, waste heat recovery, energy efficiency, drying, pasta

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1. Introduction

The industrial sector consumed globally 2751 Mtoe of energy in 2014, accounting for 29.2% of total final consumption [1]. The rising cost of electricity and environmental limitations represent an ever increasing incentive to reduce energy consumption in industrial processes. Despite significant efforts have been directed toward solutions to improve industrial energy efficiency, the average energy efficiency is 49%, with 30% of the energy input rejected as waste heat, mostly as low-grade (i.e. at temperatures below 100 °C) waste heat (42% of the total) [2]. In Italy, the Industrial Waste Heat potential has been estimated as approximately 24% of the industrial energy consumption [3], which amounted to 25.2 Mtoe in 2014 [1]. Waste heat recovery from industrial processes represents a potential measure for energy efficiency improvement providing for an abundant and sustainable alternative to costly and polluting fossil fuel sources[4–6].

Innovative technologies are progressively emerging to allow medium-high temperature heat streams to be recovered and converted into electricity. Shi et al. [7] proposed a combined power system, in which medium-high temperature waste heat can be efficiently recovered and cold energy of liquefied natural gas fully employed. Generally, below 400 °C one of the most efficient technology is based on an Organic Rankine Cycle (ORC) [8] and their optimum performance have been assessed for different working fluids under the same waste heat conditions [9]. However, while well-developed technologies are available for comparatively high-grade waste heat recovery such as ammonia/water or water/lithium bromide systems [10], low-grade heat is often rejected to the environment due to the inefficiency of these systems at temperatures below 100 °C and only recently has the focus shifted to recover this low-grade heat to improve the overall process efficiency.

Studies have assessed the opportunities for low-grade heat capture in the food processing industry with regard to economic incentives and technological advances, providing a review of the best available technologies for waste heat recovery [11, 12]. Heat exchange between same process source and sink prove to be the most feasible option for waste heat recovery, achievable with a number of well-developed heat exchangers widely available for purchase. Innovative technologies, such as the use of ORCs for electricity generation, due to high capital requirements, prove to be economically feasible as long

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as additional funding is provided.

In particular, this work focuses on the potential for low-grade waste heat recovery in the agro-food sector, being a leading industrial sector in Italy with an overall 187 billions euros turnover in 2015, a share of 11.4% of Italian GDP [13]. Agro-food industry purchases and transform approximately 72% of national raw materials, consuming approximately 11% of the annual industrial energy input [1]. It is also an ambassador of Made in Italy in the world: over the last year, export sales have reached 29.0 billions euros in 2015 [13]. In this context, the adoption of energy-saving measures in the agro-food industry assumes great importance especially with regard to dehumidification, drying and refrigeration systems where room for efficiency improvement is still considerable.

Within the agro-food industry, pasta production is of particular interest for the application presented in this paper, because of its significant energy consumption due to the drying process and because it involves large production volumes: in the first ten months of 2016, exports of pasta represented 8% of total food exports [14]. Italy is the first pasta producer in Europe, accounting for approximately three quarters of EU production [15].

The production process of alimentary pasta has been analysed in this work from both an energy and technological perspective and proved to be a suitable application for low-grade heat recovery being a non-seasonal and widespread process. Focus has been given to energy recovery systems specifically applied to the drying process that can be in perspective extended to different sectors of the industry. Indeed, the innovative methodology described in this paper is potentially applicable to the majority of drying processes powered by thermal energy, basically wherever a low-grade waste heat flow, associated with the vapour generated by the upstream process, is involved: for example, besides the food sector, drying is an important step in biomass processing [16].

Closed-cycle or heat-pump systems use the process waste heat as an input energy source and realise a thermodynamic cycle by continually repeating adsorption and desorption processes. The overall cycle efficiency depends on the adsorption system/adsorbed gas pair adopted and on operating temperatures [17].

Open cycles are based on the absorption [18] or adsorption [19–21] capability of particular materials to dehumidify the air without lowering its temperature (as opposed to conventional systems) generating significant energy savings. Adsorbent materials must be selected according to the characteristics required by the operating conditions. Among recently developed ad-

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vanced adsorbent materials, metal-organic frameworks (MOFs) compounds appear as a promising solution for low-grade waste heat capture for their high specific surface, porosity, versatility and adsorption process characteristics.

In this paper, the thermodynamic processes involved in industrial pasta drying plants have been quantitatively analysed in order to ultimately assess the energy savings that can be achieved by using adsorbent materials such as MOFs.

2. Adsorbent materials for low-grade waste heat recovery

Adsorption thermodynamic cycles can be generally divided into closed (heat pump) and open (dessication cooling) cycles.

Closed adsorption systems operate on a heat pump cycle, however, while a vapour compression cycle (mechanical heat pump) is driven by electric energy, an adsorption heat pump is driven by thermal energy. A basic heat pump adsorption cycle is made up of the following four processes [17]: heating and pressurisation; desorption and condensation; cooling and depressurisation; adsorption and evaporation.

In the first of these processes, the adsorber is heated up by a heat source and the adsorbate pressure is increased above the condensing pressure. Then, the adsorber keeps receiving heat, thus allowing the refrigerant vapour desorption (or generation). The desorbed vapour liquefies in the condenser and the latent heat is released to the first heat sink. At the beginning of the third process, the adsorber is disconnected from the condenser and then cooled by a heat transfer fluid at the second heat sink temperature, with the adsorbate pressure decreasing below evaporating pressure. Finally, the adsorber keeps releasing heat while being connected to the evaporator and its temperature continues decreasing, resulting in the adsorption of refrigerant vapour, producing the desired refrigeration effect.

A closed adsorption refrigeration cycle, being an intermittent system, requires two adsorbent beds to sequentially execute the adsorption-desorption process to achieve a continuous cooling effect: when the first adsorber performs the adsorption phase, the second adsorber will be in desorption phase.

The most important parameters to assess adsorption heat pump performance are specific power and Coefficient Of Performance (COP). The specific power is typically low for adsorption systems due to their significant cycle times and weight. The COP depends on the operating temperature and the adsorbent/adsorbate pair. Particularly, the lower the irreversibility related to

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the temperature differences of a heat transfer process, the higher the COP. Adsorbent materials feature a relatively low thermal conductivity, due to their porosity and the substantial heat transfer resistance of the low-pressure vapour surrounding the material. The thermal resistance existing at the interface between the adsorbent and heat exchanger wall is also considerably high depending on actual extension of the useful surface. This is usually very limited if, as per standard, a granular material is used. A low contact surface leads to a high thermal resistance, even higher than the internal equivalent resistance of the adsorbent bed.

On the other hand, adsorbent materials can also be effectively employed in open-cycle conditioning systems based on air drying. Contrary to conventional cooling condensation systems, in open cycles humidity can be reduced by directly adsorbing water in the form of vapour without having to lower air temperature down to the saturation temperature corresponding to the desired vapour partial pressure, leading to considerable energy savings [19–21]. Another advantage of such materials is represented by relatively low regeneration temperatures, typically below 100 °C. The possibility of exchanging both mass and heat is the greatest advantage in open-cycle systems based on adsorbent materials, since it eliminates the above-mentioned heat transfer issues and secondary circuits typical of a closed-cycle system: for this reason an open cycle has been considered in this paper.

The adsorbent material can be regenerated at temperatures of 80–100 °C, therefore low-grade waste heat sources can be effectively used. This makes the employment of these materials competitive and the adoption of advanced solutions like MOFs proves to be attractive particularly as regards the overall system footprint, which represents the main drawback of conventional adsorbent materials such as silica gel or zeolites.

Open cycle adsorption systems, and in particular solid desiccant cooling (SDC) systems, feature the following advantages [21–26]:

- SDC systems can be powered by low-grade waste heat or by renewable energies (geothermal, solar, etc);
- the process fluid is typically air and the materials employed harmless for the environment;
- drying through adsorbent materials proves to be practical and energetically inexpensive;

- SDC systems can process air with a dew point significantly lower than conventional drying systems;
- the drying process consists in an approximately isenthalpic transformation thus avoiding the energy consumption related to the post-heating process typical of conventional systems;
- solid desiccant materials do not show corrosion issues as opposed to liquid ones;
- few rotating parts, low noise and vibration levels, long duration, high reliability.

These systems can achieve a COP of 0.8–1 when activated by combustion processes while it goes down to 0.4–0.6 for helium-assisted systems. Also, air conditioning through SDC systems is a bactericidal process and eliminates dust from the process air [27].

In this study, attention has been given to potential applications of MOF materials in open adsorption cycles. Existing in a wide range of structure and chemical composition, MOFs promise to be more versatile as compared to conventional adsorption materials such as silica gel or zeolites. By varying their functional groups, adsorption characteristics can be adapted to fulfil the specific application requirements [22, 28]. Studies have assessed the potential of these materials proving them to be a promising alternative to conventional systems currently employed for air conditioning or low-grade waste heat recovery [29–31].

Precisely, what makes these materials competitive is:

- "S"-shaped isotherm that leads to thermodynamic cycles in which heat exchange processes occur at almost constant temperature. This results in an increased cycle efficiency avoiding a significant source of thermal irreversibility [32];
- high adsorption capability per unit volume and mass resulting in more compact systems.

3. Low-grade waste heat in industrial pasta drying systems

3.1. Current process description

Pasta production process consists of three different steps: kneading, shaping, and drying. While kneading and shaping processes occur within very

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compact equipment, featuring a relatively low energy consumption and high productivity, the drying process represents the bottleneck of the overall production process. In fact, over the last years significant technological efforts have been directed towards increasing the efficiency and productivity of drying processes, as also proved by several papers available in the literature on this topic [33–41]; however, a large room for improvement still exists.

The drying process of alimentary pasta can be realised in different ways, corresponding to different production layouts and operations management strategies. Particularly, as for the drying process, different operating conditions result in different temperature and moisture content of pasta and air entering/exiting the plant or recirculating within the system. However, regardless of the particular process, a generic outline of alimentary pasta production process can be drawn to analyse heat and water waste flows along with their recovery potential.

Alimentary pasta production consists of different consecutive steps: the dough mixture processing, that ends with pasta wire drawing, and the drying process. These processes take place in the kneader and in the dryer respectively. The dryer is in turn divided into different sections: the air is heated up and forced to continually recirculate to allow the water content in the dough to evaporate. Warm and humid air flows are periodically expelled and compensated by ambient air drawn into the system.

Figure 1 shows mass and energy flows for a generic pasta drying process using a black-box simplified approach.

The electric energy flow (no. 5 in the notation used in Fig. 1) is needed to power mechanical components in both sections of the plant (such as kneader, conveyor belts, fans, etc.) and can be disregarded for the purposes of this study.

On the other hand, primary energy in the form of fuel (4) is used to sustain the drying process, while heat is rejected into the environment mainly in the form of sensible and latent enthalpy of the humid and warm air flow (7) leaving the system, together with thermal dispersion, which can be significant (8), and the enthalpy of dry pasta (6 and 9). The humid air flow also retains the incoming potable water (3). Low-grade waste heat and water can be recovered downstream of the process.

The enthalpy of the air exiting the dryer is considerably high due to the significant vapour content. Recovering energy from vapour with a conventional condensation system would require the air to be cooled down to saturation. Heat would thus be recovered at temperatures too low to be

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profitably re-used within the cycle.

Alternatively, the outlet air flow could be utilised to pre-heat the dry air flow entering the desiccator (1). However, only a small amount of the available energy can be recovered due to the significant difference in the enthalpy change which the two air flows are subjected to: it is possible to show that only approximately 6% of the thermal energy of saturated air exiting the dryer at 80 °C can be recovered by heating incoming air from 20 °C to close to 80 °C.

3.2. Application of innovative adsorption materials

An original thermodynamic process, based on innovative advanced adsorbent materials, has been defined to recover low-grade waste heat and water in a generic pasta drying process.

The cycle proposed in this study results from a combination of an open cycle, where the warm, humid air exiting the dryer is the air flow to be dried, and a closed cycle (typically used in heat pump systems) where the adsorbent material regeneration occurs at relatively high temperature along with the recovery of medium-grade waste heat and water at the condenser.

Metal-organic framework compounds feature a higher affinity with water than pasta. As a result, if placed within the same space, water will naturally evaporate from the pasta dough to condense on the MOF surface. This process will continue until the adsorbent material reaches its saturation and occurs under isenthalpic evaporation conditions without significant external energy inputs.

This spontaneous effect allows a re-design of the industrial process consisting of a first step in which pasta is dried by means of vapour adsorption on MOF and a second step where the MOF is regenerated at a temperature that allows vapour condensation heat to be recovered.

To a first approximation, the first step requires thermal energy only to compensate thermal losses to the outside environment, while the second step of the process needs a medium-high thermal energy supply, which can be later recovered, albeit at a slightly lower temperature (medium temperature).

The recovered heat can be re-used within the process as an energy source for the drying process (compensating for thermal dispersion) or in other sections of the plant. The proposed process allows also the complete recovery of process water at medium temperature and in a condensed state from the condenser heat sink.

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In order to make the system operate continuously, two adsorbent beds are required to work alternately so that when the first bed is in the adsorption phase, the second adsorber performs the desorption phase and *viceversa*. Figure 2 shows a schematic of the energy flows involved in a drying process of alimentary pasta employing a low-grade waste heat recovery system based on MOF.

A comparison between Fig. 1 and Fig. 2 shows how, in a processing plant equipped with a MOF-based recovery system, the humid and warm air flow (7) is (partly or entirely) recirculated and passes above an adsorbent bed where it is dried and heated up ($7'$). This results in the reduction (or complete elimination) of the air renewal flow (1).

Dry warm air leaves the adsorber ($7'$) and flows to the dryer where it cools down providing for the heat required by the evaporation of water in the pasta. The process is almost isenthalpic: air sensible enthalpy reduction is balanced out by its latent enthalpy increase. The humid and colder air flow (7) gives off some of its water content passing above the adsorbent bed that, in turn, releases adsorption heat thus increasing air temperature. Air goes back to ($7'$) through an isenthalpic transformation: air sensible enthalpy increases while its water content decreases.

Differently from Fig. 1, in the system layout shown in Fig. 2 the high-grade heat ($4'$) generated by fuel combustion is no longer used in the medium- ($4'$a) and low-grade ($4'$b) processes but to regenerate the adsorbent material. This heat flow generates (excluding thermal losses to the environment) the medium-grade heat flows (10) and ($10'$) along with the heat flow (11) associated with the sensible heat of water recovered from the MOF regeneration process. Heat flows (10) and ($10'$) can be transferred by means of pressurised water circulating through heat exchangers in a closed-circuit.

4. Thermodynamic analysis of industrial pasta drying systems

The application case study has been conducted assuming that the drying process is the crucial step in pasta production plants from both a qualitative and quantitative perspective. The recovery system implementation, applied to the drying process, would not affect any of the process parameters (temperature, humidity, duration, *etc.*) thus avoiding a negative impact on the final product quality.

In this section, the current drying process is first quantitatively analysed, then the innovative system employing MOFs as adsorbent materials is de-

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scribed, in order to ultimately quantify the energy savings that could be achieved.

4.1. Current process description and operating parameters

Current pasta drying processes have been analysed with reference to a Braibanti desiccator [42]. Operating parameters have been calculated from values of air temperature and humidity and pasta water content available in the literature [42] as a function of the drying processing time (Figs. 3–4). Thermodynamic properties of humid air and water have been calculated by means of CoolProp thermophysical property library [43].

As shown in Figs. 3–4 the drying process is made up of different consecutive steps, precisely 1–3 representing the pre-drying sections, 4 being the actual drying process and 5 the final cooling process. Each process has a specific duration determined by a conveyor belt that carries pasta throughout the process.

Air features high humidity levels throughout the entire process, as shown in Fig. 3b, making its latent enthalpy recovery through adsorbent beds potentially highly beneficial.

Pasta water content M_w and relative humidity RH_p are fundamental process parameters for energy-related considerations and can be respectively as:

$$M_w = \frac{RH_p}{1 - RH_p} M_{dp} \tag{1}$$

$$RH_p = \frac{M_w}{M_{tot}} = \frac{M_w}{M_{dp} + M_w} \tag{2}$$

where M_{dp} is the dry portion of pasta, which remains constant throughout the production process.

As shown in Figs. 4a and 4b, a significant drop in humidity occurs in less than an hour during the pre-drying process, while over the proper drying process air humidity decreases steadily at a lower rate.

Pasta leaves the production plant with a final relative humidity of 12% and enters the desiccator with a relative humidity of 29%, resulting in an evaporation heat of approximately 156 kWh/t_{pasta}.

Each section manages in a separate way inlet and outlet air flows that are schematically represented in Fig. 5 for a generic pre-drying section. Figure 6 shows in detail mass and enthalpy flows for the same generic section.

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4.1.1. Mass balance

In the thermodynamic system analysed in this study, three different types of mass flows have to be taken into account: dry component of pasta, pasta water content and renewal air.

The dry portion of pasta $\dot{m}_{dp}$ does not change between inlet and outlet of the drying plant, hence:

$$\dot{m}_{dp,out} = \dot{m}_{dp,in} = \dot{m}_{dp} \tag{3}$$

As regards the water contained in the product, its flow at the drying outlet $\dot{m}_{w,out}$ is equal to the water flow entering the dryer $\dot{m}_{w,in}$ minus the amount of water that evaporates during the process $\dot{m}_{w,ev}$:

$$\dot{m}_{w,out} = \dot{m}_{w,in} - \dot{m}_{w,ev} \tag{4}$$

Air-vapour mixtures are typically studied with reference to dry air flow rate $\dot{m}_a$, which remains constant throughout the drying process (dry air flow at the drying outlet $\dot{m}_{a,out}$ is equal to the dry air flow entering the dryer $\dot{m}_{a,in}$) while its water vapour content varies:

$$\dot{m}_{a,out} = \dot{m}_{a,in} = \dot{m}_a \tag{5}$$

The air mass flow rate $\dot{m}_a$ only represents the renewal air introduced in the system: a significant fraction of air is recirculated, as illustrated in Fig. 5, so that the total mass flow rate of air interacting with alimentary pasta is the sum of renewal air $\dot{m}_a$ and recirculated air $\dot{m}_r$:

$$\dot{m}_{a,tot} = \dot{m}_a + \dot{m}_r \tag{6}$$

The change in air water content, defined by the difference in specific humidity between inlet and outlet $x_{out} - x_{in}$, must be equal to the evaporated water in the drying process:

$$\dot{m}_a(x_{out} - x_{in}) = \dot{m}_{w,ev} \tag{7}$$

4.1.2. Energy balance

Assuming steady-state conditions, the thermal energy balance can be expressed as:

$$\dot{Q}_{in,tot} = \dot{Q}_a - \dot{Q}_{w,l} + \dot{Q}_p = \dot{m}_a(h_{a,out} - h_{a,in}) - \dot{m}_{w,ev}h_{w,l} + \dot{m}_p c_p \Delta T_p \tag{8}$$

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The term $\dot{Q}_a$ is related to the enthalpy change of humid air between outlet and inlet $(h_{a,out} - h_{a,in})$, including a sensible enthalpy component related to the temperature increase from T_{in} to T_{out} and a latent enthalpy component due to the specific humidity change from x_{in} to x_{out}; the term $\dot{Q}_{w,l}$ is the enthalpy flow associated with water drained from the system at the desiccator pressure and temperature conditions; finally, $\dot{Q}_p$ is the heat flux absorbed by pasta, calculated with reference to the relative humidity at outlet conditions.

In order to maintain the system in a stationary state, it is necessary to provide the heat flux $\dot{Q}_{in,tot}$, which can be evaluated also as:

$$\dot{Q}_{in,tot} = \dot{Q}_{ra} + \dot{Q}_{ev} + \dot{Q}_p = \dot{m}_a \left(h^*_{a,out} - h_{a,in}\right) + \dot{m}_{w,ev}\Delta h_{ev} + \dot{m}_p c_p \Delta T_p \quad (9)$$

where $\dot{Q}_{ra}$ is the heat flux necessary to heat renewal air up to outlet temperature T_{out}, while $\dot{Q}_{ev}$ represents the heat transferred from air to pasta, required by the evaporation of a fraction of its water content. The term $h^*_{a,out}$ represents the enthalpy of humid air evaluated at temperature T_{out} and at the specific humidity of inlet air x_{in}: therefore the heat flux $\dot{Q}_{ra}$ only accounts for the sensible enthalpy change of renewal air.

In this analysis, it is not necessary to evaluate the heat flux absorbed by pasta in each of the five steps that make up the drying process, therefore only the overall thermal energy rate absorbed by pasta will be calculated. For this reason, the heat flux $\dot{Q}_{in}$ is introduced to identify the energy consumption only related to renewal air and water evaporation:

$$\dot{Q}_{in} = \dot{Q}_{ra} + \dot{Q}_{ev} \quad (10)$$

so that the total heat flux required is $\dot{Q}_{in,tot} = \dot{Q}_{in} + \dot{Q}_p$.

More specifically, an overall temperature change $\Delta T_p = 15\,\mathrm{K}$ is assumed for pasta between inlet and outlet, based on literature data [37], while the specific heat of pasta is taken as $c_p = 1.86\,\mathrm{kJ/(kg\,K)}$ [36]: consequently, the heat flux absorbed for a pasta production rate of $1\,\mathrm{t_{pasta}/h}$, which will be taken as reference in the following calculations, is $\dot{Q}_p = 7.8\,\mathrm{kWh/t_{pasta}}$.

Heat losses to the outside environment are also shown in Fig. 6: a supplementary heat flux at the desiccator inlet will be taken into account to compensate for these losses.

Air processes are shown in Fig. 7 for a generic drying section. Inlet air ("in") is mixed with the recirculating air flow ("out") at the desiccator outlet. The resulting mixed flow ("mix") must have the specific humidity required by the drying process. The flow is then heated up from "mix" to "dry"

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conditions by means of a heat exchanger. Finally, the drying transformation proceeds from "dry" to "out" at a constant wet-bulb temperature. Final relative humidity is here assumed as $\phi_{out} = 95\%$.

Figure 8 and Table 1 show respectively a graphical and numerical description of the above-mentioned processes for each drying section with reference to a pasta production rate of $1\,\mathrm{t_{pasta}/h}$. The overall thermal energy consumption for the drying process is estimated as $\dot{Q}_{in,tot} = 186.8\,\mathrm{kWh/t_{pasta}}$, not including thermal dispersions to the the surroundings.

4.2. Application of a MOF-based low-grade heat recovery

In this section, a schematic of an innovative low-grade heat recovery system based on MOFs will be outlined. Mass and energy balance will be described with reference to both adsorption and regeneration processes.

In order to allow the process to be continuous, each section will be equipped with two adsorption beds operating alternately so that when the first bed is in the adsorption phase, the second adsorber is regenerated, and *vice versa.*

4.2.1. Adsorption process

Adsorption is the active process, where humid and warm air, flowing above the adsorbent bed, releases a fraction of its water content and a corresponding heat flux given by:

$$\dot{Q}_{ads} = \dot{m}_{w,ads} \Delta h_{ads} \tag{11}$$

where $\dot{m}_{w,ads}$ is the adsorbed water flow and Δh_{ads} is the enthalpy change related to the adsorption process, which is a property of the adsorbent material but it can be assumed, to a first approximation, equal to water evaporation enthalpy. Thus, air is heated up and dehumidified during the process, which basically provides the heat flux $\dot{Q}_{in}$ required by the drying process.

Figure 9 shows a schematic of the proposed solution with reference to a single drying section. Air is drawn again into the system upon being dried by the MOF and mixed with a recirculation flow. Air mass flow rate has to be such that the functional parameters of the process (temperature, air and pasta humidity, duration, air flow) are not affected.

Air properties have been assessed in each drying section at the adsorbent bed inlet and outlet, points a and b on the psychrometric chart represented in Fig. 10. Air conditions after being mixed with the recirculation flow have also been represented for each section.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

The air flow to be processed $\dot{m}_{ads}$ can be derived by imposing that the air flow entering each section must be equal to the mass flow rate $\dot{m}_{a,tot}$ calculated for a conventional process (see Table 1), and that the water adsorbed by MOFs, given by $(x_a - x_b)\,\dot{m}_{ads}$, must be equal to the water released by pasta in the drying process, given by $(x_a - x_{dry})\,\dot{m}_{a,tot}$:

$$\dot{m}_{ads} = (x_a - x_{dry})/(x_a - x_b)\,\dot{m}_{a,tot} \tag{12}$$

In this way the functional parameters of the process are respected intrinsically guaranteeing the equivalence between the water flow rate evaporated from pasta and the water adsorbed by the MOF bed.

Results are listed in Table 2 in terms of temperature, relative humidity, mass and energy flows. As previously mentioned, the cooling section can be energetically disregarded, thus only pre-drying (sections 1 to 3) and drying (section 4) processes have been considered and the corresponding results given in Table 2. The results obviously confirm, given the assumptions, that heat recovered during the adsorption is exactly equal to the heat required by the drying process: the total value of $\dot{Q}_{ads}$ in Table 2 is indeed the same as the evaporation heat $\dot{Q}_{ev}$ given in Table 1 once the cooling section is included in the calculation. In the proposed system layout, renewal air is no longer needed, therefore the heat flux $\dot{Q}_{ra}$ required by its sensible enthalpy change must not be supplied. Finally, the adsorption process is graphically described on a psychrometric chart in Fig 10.

4.2.2. Regeneration process

The regeneration process is required to bring the adsorbent bed back to its initial state. Thus, thermal energy has to be supplied to allow the evaporation of adsorbed water. In this specific case, the regeneration process will be realised at temperatures sufficiently high to make the recovered heat re-usable within the drying process itself or in other processes within the same plant.

Figure 11 shows a schematic of the regeneration system, where an intermediate reheating process is considered in order to limit the maximum temperature to be reached by the regeneration air flow (section 1).

While in the adsorption process all functional parameters had to remain unchanged, this restriction is no longer required in the regeneration process. Therefore, adsorbent beds of each drying section can be analysed with reference to the same regeneration process. In other words, adsorbent beds

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

belonging to different sections can be regenerated in parallel using a single recovery heat exchanger along with one condenser, one main heater (heater 1 in Fig. 11) and as many auxiliary heaters (heater 2 in the schematic) as the number of the MOF beds. This all contributes to optimise the plant design.

The MOF bed is regenerated by means of a warm humid air flow $\dot{m}_{a,reg}$. To allow the water desorption from the adsorbent bed, the vapour partial pressure within the air flow has to be lower than the adsorbed water partial pressure. Therefore, air relative humidity has to be lower than the MOF-specific adsorption threshold α (later defined in section 4.4) at the regeneration temperature T_{reg}. To a first approximation, the heat required by the process is equal to the evaporation heat of the adsorbed water.

The recovery heat exchanger (identified as REC in Fig. 11) is used to recover most of the superheated air sensible heat to pre-heat the air flow before it reaches the heater. Once the heat exchanger effectiveness ϵ is specified, the behaviour of the component is described by the following equations:

$$T_{4'} = T_4 + \epsilon\,(T_2 - T_4) \tag{13}$$

$$\dot{Q}_{REC} = \dot{m}_{a,reg}(h_{4'} - h_4) = \dot{m}_{a,reg}(h_2 - h_{3'}) \tag{14}$$

The condenser (3′–4 process) is required to recover the evaporation heat supplied to the air flow during the regeneration process. A small amount of sensible heat needs to be taken into account for the pre-cooling necessary to reach saturation conditions (process 3′–3) and for the humid air temperature drop along the condensation process (3–4). The condensation process allows the process water, previously adsorbed by the MOF and evaporated from pasta, to be recovered at technologically useful temperatures. Condensation heat is transferred to a water flow ($\dot{m}_{w,cond}$), at a temperature that is compatible with its later use in technological processes. Mass and energy conservation equations for this component are:

$$\dot{m}_{a,reg}(x_3 - x_4) = \dot{m}_{w,reg} \tag{15}$$

$$\dot{Q}_{w,cond} = \dot{m}_{w,cond}\, c_w\, \Delta T_{w,cond} = \dot{m}_{a,reg}(h_{3'} - h_4) - \dot{m}_{w,reg} h_{w,reg} \tag{16}$$

The energy conservation equation can be alternatively written as follows:

$$\begin{aligned}\dot{Q}_{w,cond} = {} & \dot{m}_{w,reg}\Delta h_{ev}(T_3) + \dot{m}_{w,reg} c_w (T_3 - T_4) + \\ & + \dot{m}_{a,reg}(h_{3'} - h_3) + \dot{m}_{a,reg}(h_3^* - h_4)\end{aligned} \tag{17}$$

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

where h_3^* is the enthalpy of humid air evaluated at temperature T_3 and specific humidity x_4 (humidity value at the end of the condensation process). In this way, the first term on the right hand side represents the latent heat related to vapour condensation occurring at temperature T_3; the second term is related to the sensible enthalpy decrease as saturated liquid cools down from T_3 to T_4; the third represents the desuperheating heat flux $\dot{Q}_{SH}$, i.e. the sensible enthalpy change of humid air entering the condenser as it is cooled down to saturation conditions; the fourth term is related to the sensible enthalpy decrease of humid air leaving the condenser due to the temperature drop taking place during condensation.

The mass flow rate of water recovered at the condenser must be the same that had been adsorbed by the MOF beds in the adsorption process: $\dot{m}_{w,reg} = \dot{m}_{w,ads}$.

Finally, the heater, powered by a boiler, is divided into a main section (heater 1) and few other intermediate reheating sections, one for each bed (heater 2), and provides for the necessary heat to accomplish the entire regeneration process:

$$\dot{Q}_{heat,reg} = \dot{m}_{a,reg}(h_1 - h_{4'}) + \dot{m}_{a,reg}(h_{1'} - h_{2'}) \tag{18}$$

Besides the heat flux required by the regeneration process, given by the equation above, it is necessary to take into account that the water contained in the processed pasta is heated up from drying to condensing temperature. This contribution must be added to the heating power necessary to accomplish the regeneration process and can be evaluated as follows (subscript wp identifies quantities related to pasta water content):

$$\dot{Q}_{wp} = \dot{m}_{w,reg}\, c_w\, (T_{cond} - T_{dry}) \tag{19}$$

$$\dot{Q}_{heat,tot} = \dot{Q}_{heat,reg} + \dot{Q}_{wp} \tag{20}$$

The regeneration process has been assessed taking into account the operating parameters specified in Table 3. Here, MOF properties are summarised in the parameter $\alpha_{T_{ref}}$, which represents the adsorption threshold as explained later in section 4.4.

Partial pressure of dry air has been taken as a weighted average of the partial pressures existing in each drying section: the different sections work in parallel during the adsorption phase, determining different partial pressures for dry air and vapour depending on the specific operating conditions, but

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

they are instead connected in series for the regeneration process, therefore pressure differences are eliminated. The weights in the weighted average are given by the ratio of adsorbed water in the specific section to the overall adsorbed water in the entire process.

The characteristic points of the cycle have thus been derived from the conservation equations detailed above and are shown in Fig. 12 on a psychrometric chart for a condensing temperature of 95 °C.

Values of heat flux exchanged in each component can be derived from the air flow rate (given by eq. 15) and are represented in the heat exchange diagram of Fig. 13 again for a condensing temperture (T_4) of 95 °C. Condensation and desuperheating processes are shown separately on the graph; the air flow is represented in blue and the water flow at the condenser in black.

Finally, Table 4 sums up the results obtained from the analysis of the regeneration process, evaluated according to the mass and energy balance equations detailed above, for different values of condensing temperature.

4.3. Energy savings assessment

4.3.1. Thermal energy savings

The adoption of adsorbent beds allows to dehumidify the humid air leaving the drying unit, making it available again to the dryer, without any external heat input in the adsorption process; in a conventional process the sensible and latent enthalpy of humid air would be otherwise lost with the renewal air flow rejected into the environment.

Heat must then be used for the regeneration of adsorbent beds, but it is almost entirely recovered at the condenser at a temperature that makes it suitable for the drying process in order to make up for heat losses and thermal dispersion to the surroundings. This results in significant energy savings with reference to a conventional drying process.

In order to assess the energy savings that could be obtained with the proposed system, it is necessary to estimate the actual total energy consumption in a real case, which includes the heat flux required by the drying process, quantified in 186.8 $\mathrm{kWh/t_{pasta}}$ in section 4.1, and other thermal energy losses (mainly thermal dispersion to the environment). Brunetti *et al.* [40] measured the energy consumption of a small Italian plant producing fresh pasta and found that the drying cabinet required 242 $\mathrm{kWh/t_{pasta}}$. Wang *et al.* [41] conducted an energy analysis of a tunnel dryer for dried Chinese noodles and found an energy consumption of 205 $\mathrm{kWh/t_{pasta}}$. Panno *et al.* [15] gave a range of 250–470 $\mathrm{kWh/t_{pasta}}$. Ozgener [36] analysed data from an industrial

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

pasta drying process plant in Turkey finding an energy efficiency of around 69% (i.e. 31% of the energy input was lost as thermal dispersion to the surroundings): using this energy efficiency value in the present case, we would obtain an overall energy consumption of $186.8/0.69 = 270.7\,\mathrm{kWh/t_{pasta}}$, a value in line with the above-mentioned data retrieved from the scientific literature. Technical reports (mainly environmental impact assessments) by some Italian pasta manufacturers can be seen as broadly confirming these data, since they point to values of primary energy consumption in the range 323 to $525\,\mathrm{kWh/t_{pasta}}$, and this energy consumption includes several other processes beyond drying [44–47].

In order to provide a conservative assessment of the possible energy savings, the energy efficiency of a conventional drying process has been taken here as 60%, resulting in a total energy consumption $Q_{tot} = 311.3\,\mathrm{kWh/t_{pasta}}$; with this assumption, thermal dispersion to the surroundings amounts to $Q_l = 124.5\,\mathrm{kWh/t_{pasta}}$ (Table 5).

If compared to a conventional system, the proposed configuration could introduce additional thermal dispersion to the outside environment due to both adsorption and regeneration processes. However, these additional heat losses have not been assessed as of difficult evaluation in this analysis. Besides, they can be assumed lower by at least an order of magnitude than the heat losses in the drying process because surfaces and volumes of the adsorption and regeneration sections are significantly smaller than those of the drying section. Furthermore, the sensible heat loss due to the bed transition from the adsorption to the regeneration process has been disregarded, actually being not dissipated but recovered in the following adsorption process.

Figure 14 represents a schematic of a possible solution to re-use the recovered heat $\dot{Q}_{w,cond}$ to compensate for heat losses. Since the adsorption process already recovers the heat flux required by the drying process (see section 4.2.1), the heat flux recovered from the condenser in the regeneration process can be largely re-used within the cycle ($\dot{Q}_{rec}$ in the figure) at the temperature $T_{w,out}$, and it can be either higher or lower than the heat necessary to keep the cycle in stationary conditions, leading respectively to a surplus or to the need of a make-up heat, depending on the amount of thermal dispersion to the surroundings.

It is also possible to recover heat from the sensible enthalpy of water drained at the condenser, but this recovery takes place at temperatures that are too low to be re-usable within the process; nonetheless, it can be used for other purposes such as pasta dough heating at 40 °C.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

Table 6 lists relevant heat flux values as a function of condensing temperature for the assessment of energy savings, which are presented in the same table both with and without taking into account the possible recovery of surplus heat in the industrial facility (recovery from condensate is on the contrary neglected in both cases). The results show that thermal energy savings of around 40–50% can be achieved with the adoption of the proposed system based on adsorbent beds.

4.3.2. Electrical consumption

As discussed above, the adoption of an adsorption cycle allows a significant decrease in overall thermal energy consumption. However, this has to be compared with the increased electricity demand due to the higher ventilation load. Such consumption has been estimated with reference to already existing drying plants.

Environmental impact assessments provided by Italian pasta manufacturers allow to estimate the total electric energy consumption for an industrial pasta processing plant in approximately $180\,\mathrm{kWh/t_{pasta}}$, a value in line with the BAT range of 140–$220\,\mathrm{kWh/t_{pasta}}$ set by environmental regulations [44–47]. Most of the electric energy consumption is due to the operation of kneader, conveyor belts and other equipment in the production and drying units, while the consumption of fans for air circulation is only a small fraction of the total: more specifically, it can be quantified in approximately 10% of the total [44], or $18\,\mathrm{kWh/t_{pasta}}$.

If we assume that fans process the same air flow in the adsorption system as in a conventional drying plant, with the only difference that air flows through the adsorbent bed rather than a heat exchanger and that extraction fans would not be required, the increase in electricity consumption related to the adsorption process can reasonably be neglected.

On the contrary, additional fans are required to accomplish the regeneration process leading to an energy consumption comparable or slightly higher than the drying process.

Taking into account that blowing air through the adsorbent bed may increase the load because of larger pressure losses, it can be conservatively assumed that in the proposed system fans electrical consumption could increase to approximately $50\,\mathrm{kWh/t_{pasta}}$, all other electric energy loads being equal.

In terms of overall energy balance, results are particularly interesting as a drying system with low-grade waste heat recovery would require a thermal

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

and electric load (for air circulation) of respectively 176.2 and 50 kWh/t$_{\mathrm{pasta}}$, as opposed to 311.3 and 18 kWh/t$_{\mathrm{pasta}}$ for a conventional drying plant. The large reduction in thermal energy more than compensate for the increase in electric energy consumption: indeed, if we consider the primary energy needed (in terms of fuel energy), taking into account a 90% efficiency for the boiler and a 46% efficiency for the power plant generating electricity[1], the proposed system requires 304.4 kWh/t$_{\mathrm{pasta}}$, while a conventional one 385.0 kWh/t$_{\mathrm{pasta}}$, with a corresponding reduction in primary energy consumption of approximately 20%.

Thus, by implementing the proposed solution a significant energy efficiency improvement in the drying process of alimentary pasta can be obtained. This is achieved by reducing the thermal load required by the drying process, recovering within the process almost all the waste heat generated within the process, while slightly increasing electric energy consumption.

Further advantages in terms of energy efficiency can be achieved by coupling the proposed solution with a Combined Heat and Power system [15, 19]. Currently existing techno-economic limitations related to the significant difference between thermal and electric load in a conventional drying plant can be partially levelled out with the adoption of a waste heat recovery system based on adsorbent material.

4.4. MOF properties

Along with the functional parameters imposed by the process, the physical properties of MOFs have to be considered. Such materials feature an adsorption threshold defined by the parameter:

$$\alpha = p/p_{sat} \tag{21}$$

where p is the vapour pressure and p_{sat} is the saturation pressure at a given temperature. The parameter α depends on temperature as follows:

$$\alpha_T = \alpha_{T_{ref}}^{T_{ref}/T} \tag{22}$$

with $\alpha_{T_{ref}}$ assumed equal to 0.45 at reference temperature $T_{ref} = 20\,^{\circ}\mathrm{C}$. Figure 15 compares an adsorption isotherm expressed by the uptake in terms of grams of adsorbed substance to grams of adsorbent material for a real MOF (blue) with the theoretical approximation used in this study (red dotted line).

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[1] average efficiency for Italian thermoelectric generation

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

In order to be successfully employed within the proposed drying process of alimentary pasta, the adsorbent material has to satisfy the following requirements:

- water adsorption capability;
- able to perform a high number of working cycle (ideally 100 000);
- high specific adsorption capacity, known as uptake, between initial and final conditions. This parameter is inversely proportional to the number of working cycle and, therefore, to the estimated material useful life;
- high reaction kinetic. This affects the specific power and, therefore, the amount of material to be used to achieve the required power as well as initial costs and volumes;
- type-IV and V adsorption isotherm according to IUPAC classification [22] with high slope in the adsorption-desorption transition and low hysteresis effects;
- physical and chemical compatibility with food processing and with interacting substances in the process;
- continuous operation at high temperatures (150–160 °C).

In this study, system layout and design assumptions impose specific constraints on possible values of the parameter α, and in particular the higher limit is dictated by the adsorption process and depends on air relative humidity, while the regeneration process provides the lower limit.

Beginning with the adsorption process, if the MOF is to be able to dry air, it has to feature an α value lower than air relative humidity, which ranges between 69.8% and 77.1% (ϕ_{dry} in Table 1): therefore, α upper limit can be considered equal to 60–65% at 20 °C.

With reference to the regeneration process, in this case the lower threshold value on α does not depend on the process itself but rather it can be imposed by setting a limit on the ratio between sensible and latent heat recovery in the condenser (Fig. 13): in particular, a decrease in sensible heat $\dot{Q}_{SH}$ reduces the irreversibility involved in the heat exchange process. By setting this ratio at a maximum value of 20%, and calculating the new operating conditions for the regeneration process (and in particular new values for regeneration

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

temperature T_{reg}), minimum values of α at a reference temperature of 20 °C for the proposed application range from 15% to 39% depending on the choice of condensing temperature (Table 7).

The feasibility of the project has been verified with reference to type-IV and V advanced adsorbed materials, with a high slope in the desorption-adsorption transition and low hysteresis effects: MOFs feature all of these characteristics.

To guarantee the technical feasibility of the proposed methodology, the adsorbent material has to meet further requirements:

- long useful life in terms of number of complete adsorption-desorption cycles performed;
- high thermal stability, with the capability of working continuously at high temperature (150–160 °C) in presence of superheated vapour;
- high specific adsorption capacity (uptake);
- optimal adsorption-desorption kinetics;
- α limit values between a minimum of 15 and 40 % and a maximum of 60 and 65 % depending on the specific application;
- with reference to pasta production process, the material has to be alimentary and chemically compatible with the interacting substances.

MOFs with the required chemical and physical properties, as mentioned above, are indeed available: a first survey pointed out to materials such as MIL-100(Fe), MIL-53(Al), Al-fumarate and CAU-10-H [48–50] which do not contain any heavy metals and thus are potentially compatible with food processing. Such materials will be tested for the application here described in a follow-up of this work.

5. Conclusions

This study focused on energy efficiency solutions applied to industrial pasta drying plants by employing a low-grade waste heat recovery system based on advanced adsorbent material with high specific surface (Metal Organic Framework, MOF).

An innovative methodology has been defined, based on recovering latent heat downstream of pasta drying process and the related energy savings have

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

been assessed. The application of innovative adsorbent materials to regenerate warm and humid air flow makes the heat released by vapour adsorption immediately available to the process, allowing a continuous recirculation of thermal energy supply.

The adsorbent material must be regenerated at high temperature, but the thermal energy supplied for regeneration can be in turn recovered by condensing the water evaporated from the adsorbent material at a temperature sufficiently high to be usefully recovered within the same process or elsewhere. Moreover, process water can be recovered downstream of the condenser and sent back to the kneader or re-used for other purposes within the process.

Low-grade waste heat recovery slightly increase the overall electric load, but this increase is more than compensated for in terms of primary energy by the reduction in thermal energy consumption.

Energy savings achievable by implementing a drying system with low-grade waste heat recovery based on MOF have been assessed. For a conventional drying plant with 60% efficiency, a thermal load of $311.3\,\mathrm{kWh/t_{pasta}}$ can be estimated, where the power actually used for the drying process is $186.8\,\mathrm{kWh/t_{pasta}}$, while $125.5\,\mathrm{kWh/t_{pasta}}$ are required to compensate for heat losses. The adoption of the proposed methodology would lead to a reduction of approximately 40% of the total energy load for the drying process.

To further validate these theoretical results, MOFs materials will be tested for the application here described in a follow-up of this work where experimental tests will be also carried out to investigate the system behavior under different operating conditions.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

Nomenclature

c_p	specific heat at constant pressure [kJ/(kg K)]
h	enthalpy [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
M	mass [kg/$\mathrm{t_{pasta}}$]
p	pressure [kPa]
$\dot{Q}$	heat flux [kW]
RH	pasta relative humidity [%]
T	temperature [°C]
x	air specific humidity [$\mathrm{kg_v/kg_a}$]

Greek letters

α	MOF adsorption threshold
ϵ	recovery heat exchanger effectiveness
ϕ	air relative humidity [%]

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

Superscripts and subscripts	
a	air
ads	adsorption
cond	condensation
dp	pasta (dry basis)
ev	evaporation
in	inlet section of the plant
l	latent
out	outlet section of the plant
p	pasta
r	recirculated air
ra	renewal air
REC	recovery heat exchanger
reg	regeneration
SH	desuperheating
v	vapour
w	water
wp	pasta water content

Acronyms	
COP	Coefficient Of Performance
HEX	Heat exchanger unit
MOF	Metal Organic Framework
SDC	Solid Desiccant Cooling

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Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

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Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

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Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

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Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

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Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

List of Tables

List of Figures

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

Parameter	Value in each drying sections					Total
	1	2	3	4	5	
Temperature [°C]						
T_{in}	20.0	20.0	20.0	20.0	20.0	
T_{mix}	38.9	51.2	63.1	64.6	30.0	
T_{dry}	44.0	58.0	68.0	70.0	34.0	
T_{out}	39.8	52.2	63.6	65.1	30.7	
Relative humidity [%]						
ϕ_{in}	50.0	50.0	50.0	50.0	50.0	
ϕ_{mix}	95.9	96.8	96.1	96.2	94.1	
ϕ_{dry}	73.3	69.8	77.1	75.7	74.9	
ϕ_{out}	95.0	95.0	95.0	95.0	95.0	
Mass flow rate [kg/s]						
$\dot{m}_{w,ev}$	0.012	0.013	0.012	0.029	0.001	0.066
$\dot{m}_{a}$	0.303	0.153	0.071	0.156	0.032	0.715
$\dot{m}_{r}$	5.877	4.328	4.656	9.871	0.411	25.140
$\dot{m}_{a,tot}$	6.180	4.481	4.727	10.03	0.443	25.860
Heat flux [kW]						
$\dot{Q}_{ev}$	28.26	31.00	28.33	68.24	1.54	157.4
$\dot{Q}_{ra}$	6.09	4.98	3.12	7.11	0.35	21.6
$\dot{Q}_{a}$	36.31	38.82	34.65	83.27	1.97	195.0
$\dot{Q}_{w,l}$	1.96	2.85	3.21	7.92	0.08	16.0
$\dot{Q}_{in}$	34.35	35.98	31.45	75.35	1.89	179.0
$\dot{Q}_{p}$						7.8
$\dot{Q}_{in,tot}$						186.8

Table 1: Air temperature, relative humidity, mass flow rates and heat fluxes in each drying section (with reference to a pasta production rate of $1\,\mathrm{t_{pasta}/h}$).

Parameter	Value in each drying sections				Total
	1	2	3	4	
Temperature [°C]					
T_a	39.8	52.2	63.6	65.1	
T_{dry}	44.0	58.0	68.0	70.0	
T_b	50.8	64.6	77.1	78.7	
Relative humidity [%]					
ϕ_a	95.00	95.00	95.00	95.00	
ϕ_{dry}	73.30	69.80	77.10	75.70	
ϕ_b	48.60	50.00	51.30	51.40	
Mass flow rate [kg/s]					
$\dot{m}_{ads}$	2.37	2.17	1.63	3.810	9.980
$\dot{m}_{rec}$	3.81	2.31	3.10	6.220	15.440
$\dot{m}_{a,tot}$	6.18	4.48	4.73	10.030	25.420
$\dot{m}_{w,ads}$	0.012	0.013	0.012	0.029	0.066
$\dot{Q}_{ads}$ [kW]	28.26	31.00	28.33	68.24	155.83

Table 2: Air temperature, relative humidity, mass flow rates and adsorption heat flux for the adsorption process in each drying section (with reference to a pasta production rate of $1\,\mathrm{t_{pasta}/h}$).

Parameter		Value
Condensing temperature	$T_4 = T_{cond}$	95 to 125 °C
Regeneration air maximum temperature	$T_{\max}$	160 °C
Recovery heat exchanger effectiveness	ϵ	0.70
Approach ΔT at the condenser cold end	$\Delta T_{app} = T_4 - T_{w,in}$	10 °C
Pinch-point ΔT at the condenser	ΔT_{pp}	5 °C
Air partial pressure	p_a	83.6 kPa
MOF adsorption threshold	$\alpha_{T_{ref}}$	0.45

Table 3: Parameters and assumptions used in the regeneration process analysis.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

Parameter	Value			
T_{cond} [°C]	95	105	115	125
Pressure [kPa]				
p_a	83.6	83.6	83.6	83.6
p_v	84.6	120.9	169.2	232.2
p_{tot}	168.2	204.5	252.8	315.9
Heat flux [kW]				
$\dot{Q}_{w,cond}$	161.3	162.1	165.2	175.2
$\dot{Q}_{REC}$	22.3	28.3	39.8	67.5
$\dot{Q}_{heat,reg}$	160.8	161.8	165.0	175.0
$\dot{Q}_{wp}$	15.5	18.2	21.0	23.8
$\dot{Q}_{heat,tot}$	176.2	180.0	186.1	198.9
Temperature [°C]				
$T_2 = T_{reg}$	114.5	124.4	134.5	144.8
$T_{w,in}$	85.0	95.0	105.0	115.0
$T_{w,out}$	92.2	101.6	111.3	121.4
Mass flow rate [kg/s]				
$\dot{m}_{a,reg}$	0.706	0.717	0.781	1.005
$\dot{m}_{w,reg}$	0.066	0.066	0.066	0.066
$\dot{m}_{w,cond}$	5.225	5.750	6.156	6.450

Table 4: Results of the regeneration process analysis with intermediate reheating (with reference to a pasta production rate of $1\,\mathrm{t_{pasta}/h}$) for different condensing temperatures.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

Energy consumption [kWh/t_{pasta}]		
Overall energy consumption	Q_{tot}	311.3
Drying energy consumption	$Q_{in,tot}$	186.8
Heat loss	Q_l	124.5

Table 5: Reference energy consumption for a conventional drying plant with 60% efficiency.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

Parameter	Value			
T_{cond} [°C]	95	105	115	125
Heat flux [kW]				
$\dot{Q}_{rec}$	161.3	162.1	165.2	175.2
$\dot{Q}_l + \dot{Q}_p$	132.3	132.3	132.3	132.3
$\dot{Q}_{surplus}$	29.0	29.8	32.9	42.9
$\dot{Q}_{make-up}$	0.0	0.0	0.0	0.0
$\dot{Q}_{heat,tot}$	176.2	180.0	186.1	198.9
$\dot{Q}_{boiler}$	176.2	180.0	186.1	198.9
$\dot{Q}_{boiler,ref}$	311.3	311.3	311.3	311.3
Energy savings [%]	43.4	42.2	40.2	36.1
incl. surplus heat	52.7	51.8	50.8	49.9

Table 6: Heat flux values and energy savings in a real case application (with reference to a pasta production rate of $1\,\mathrm{t_{pasta}/h}$); $\dot{Q}_{boiler,ref}$ represents the energy consumption in a conventional drying plant with 60% efficiency.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

Parameter	Value			
T_{cond} [°C]	95	105	115	125
p_{tot} [kPa]	168.20	204.50	252.80	315.90
T_{reg} [°C]	137.90	141.30	144.60	148.20
$\alpha_{T_{reg}}$ [%]	25.90	33.20	42.00	51.90
$\alpha_{20\,°\mathrm{C}}$ [%]	15.00	21.00	29.00	39.00

Table 7: Lower threshold values for α obtained by limiting the desuperheating heat flux ratio.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

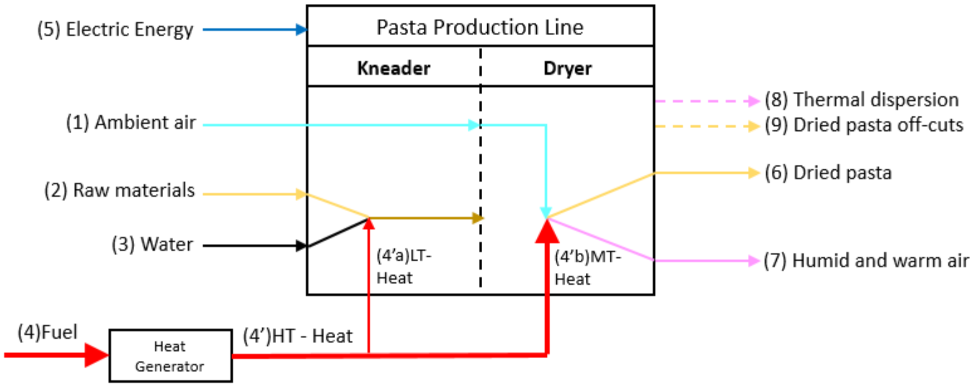

Figure 1: Schematic of energy and mass flows for a generic drying process of alimentary pasta.

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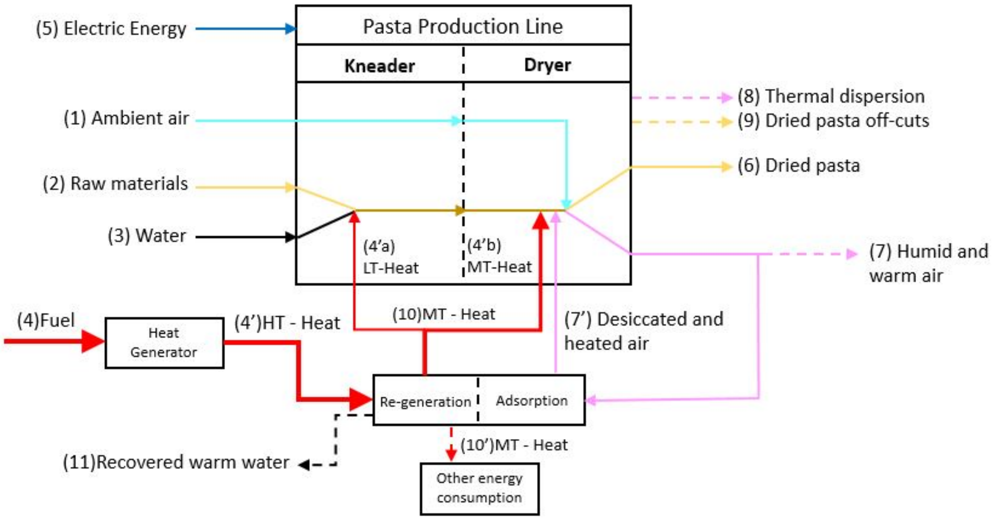

Figure 2: Schematic of energy and mass flows in a drying process of alimentary pasta with low-grade waste heat recovery based on MOF.

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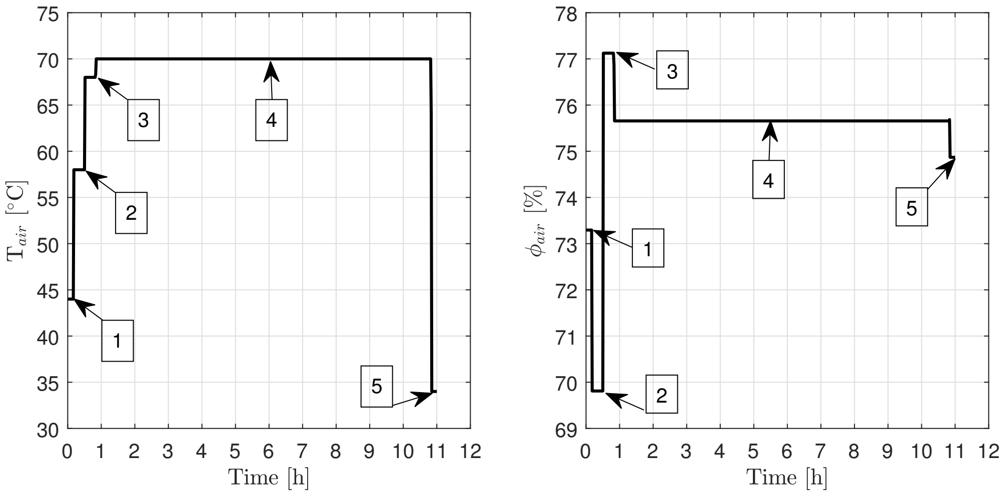

(a) Air temperature (b) Air relative humidity

Figure 3: Air temperature and relative humidity throughout the different drying process steps: 1–3: pre-drying; 4: drying; 5: final cooling.

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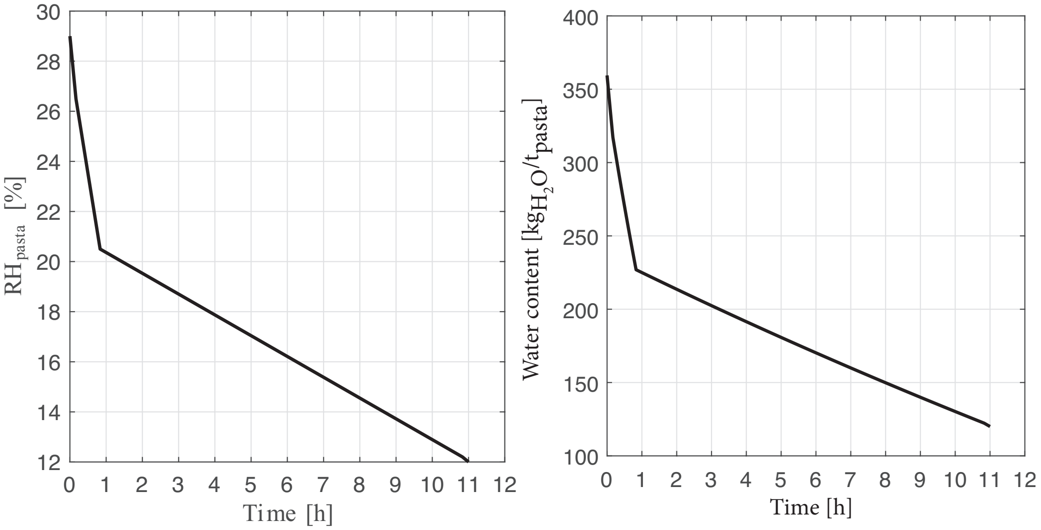

(a) Pasta relative humidity

(b) Pasta specific humidity

Figure 4: Pasta relative humidity and water content throughout the drying process.

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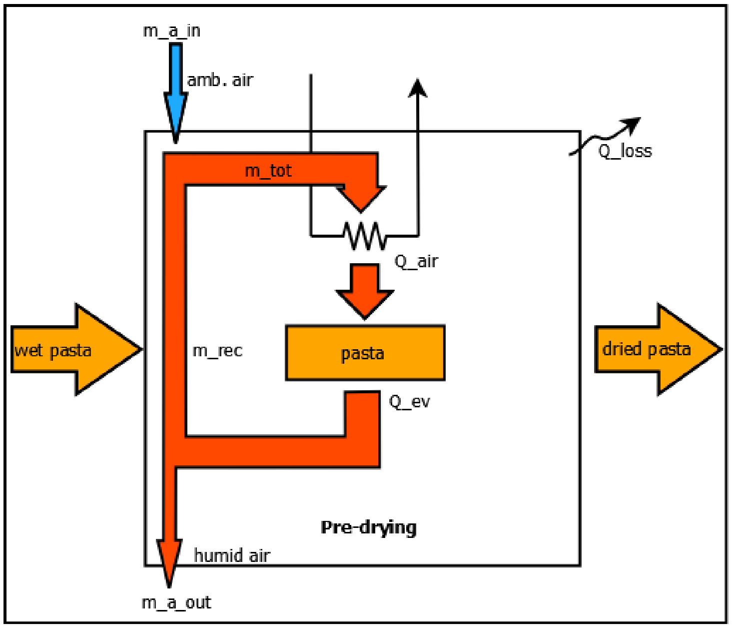

Figure 5: Air flows for a generic section of the drying process.

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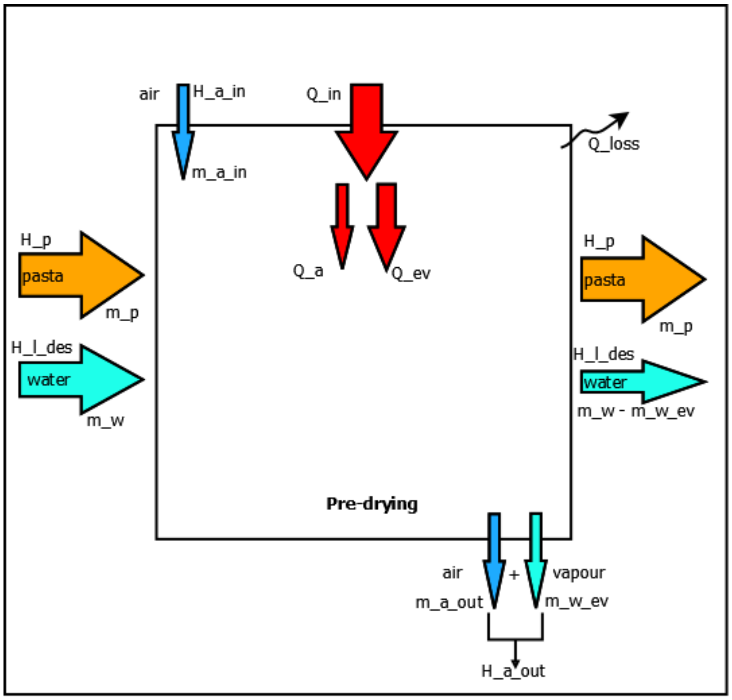

Figure 6: Mass and enthalpy balance for a generic section of the drying process.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

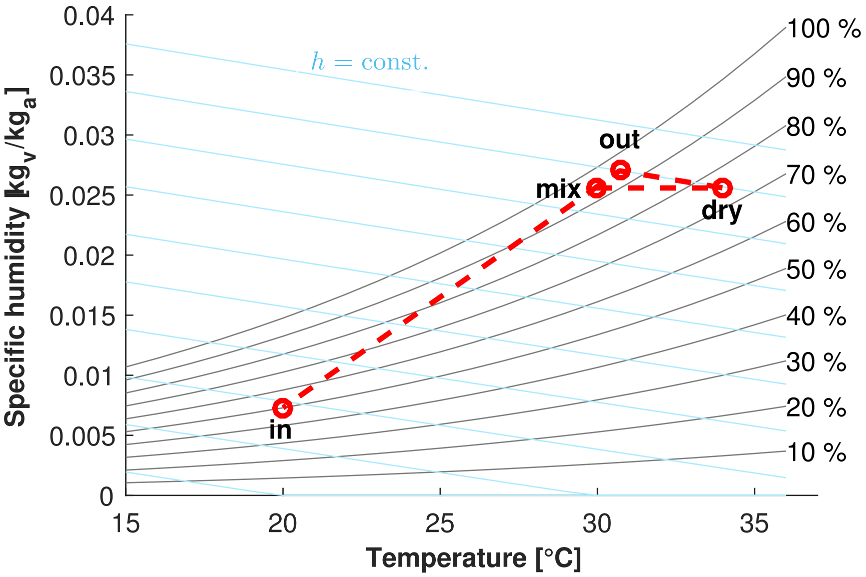

Figure 7: Air processes for a generic drying section on a psychrometric chart.

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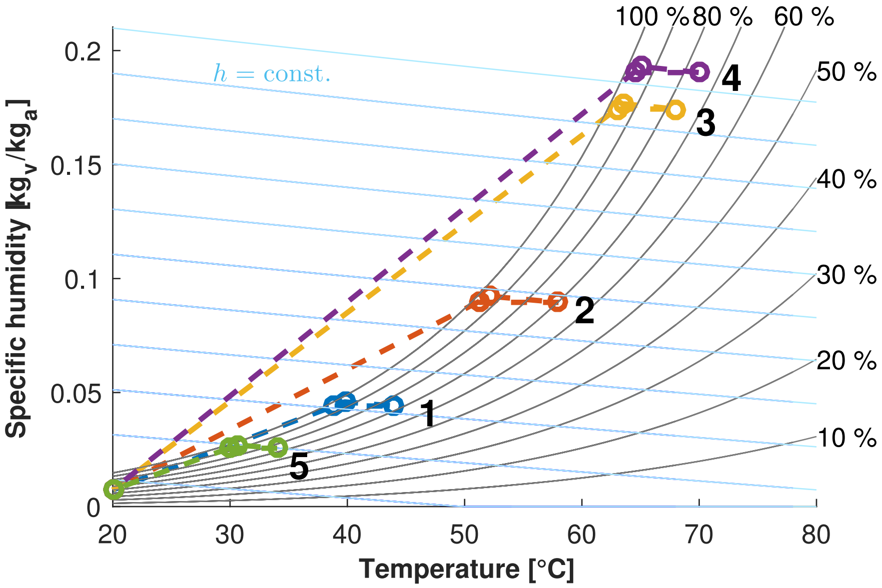

Figure 8: Air transformations in each drying section displayed on a psychrometric chart.

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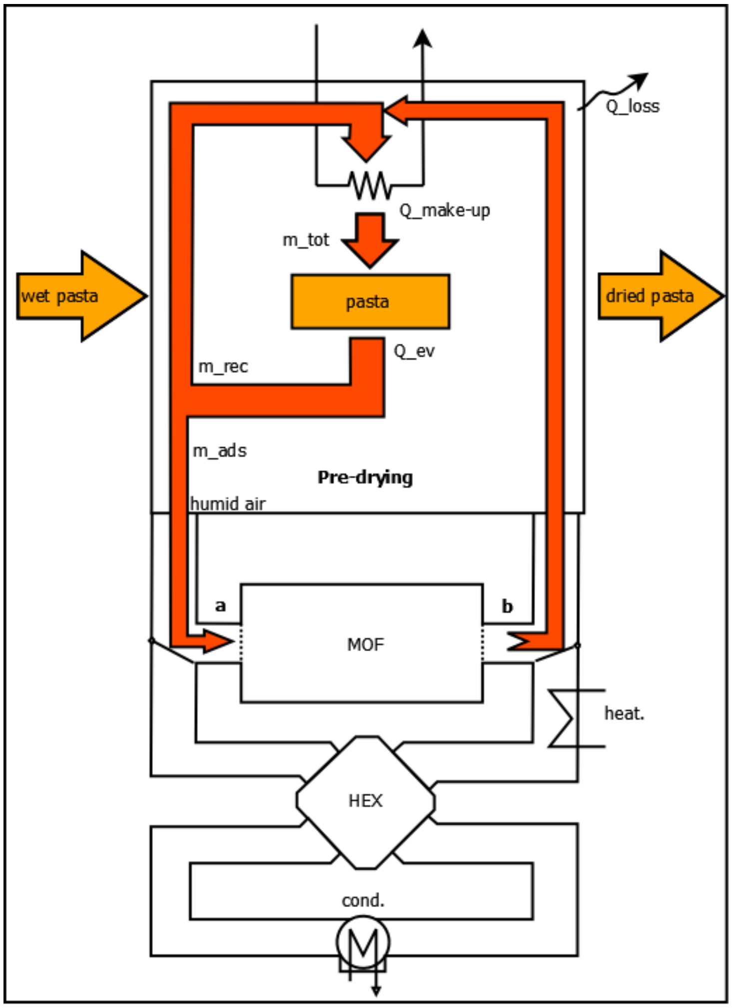

Figure 9: Schematic representation of the proposed solution for a single drying section.

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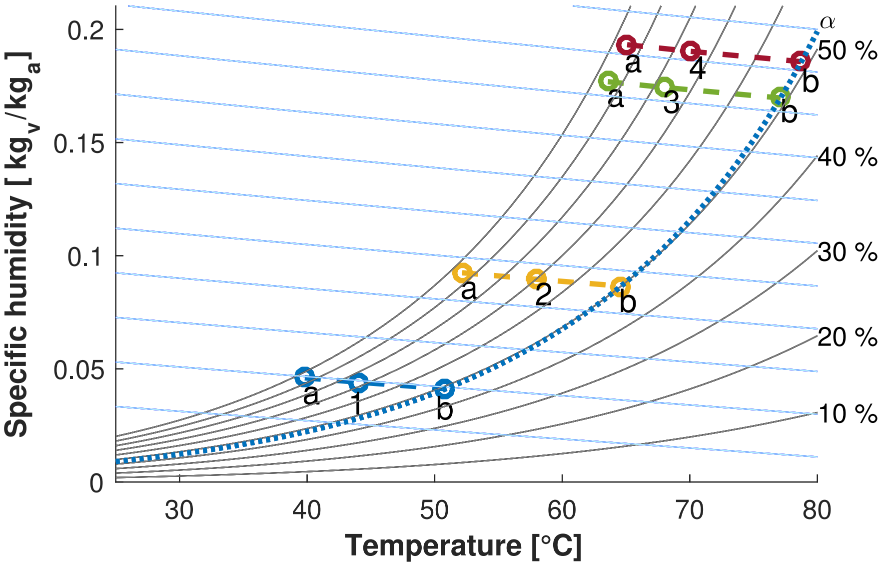

Figure 10: Adsorption process on a psychrometric chart for the different sections.

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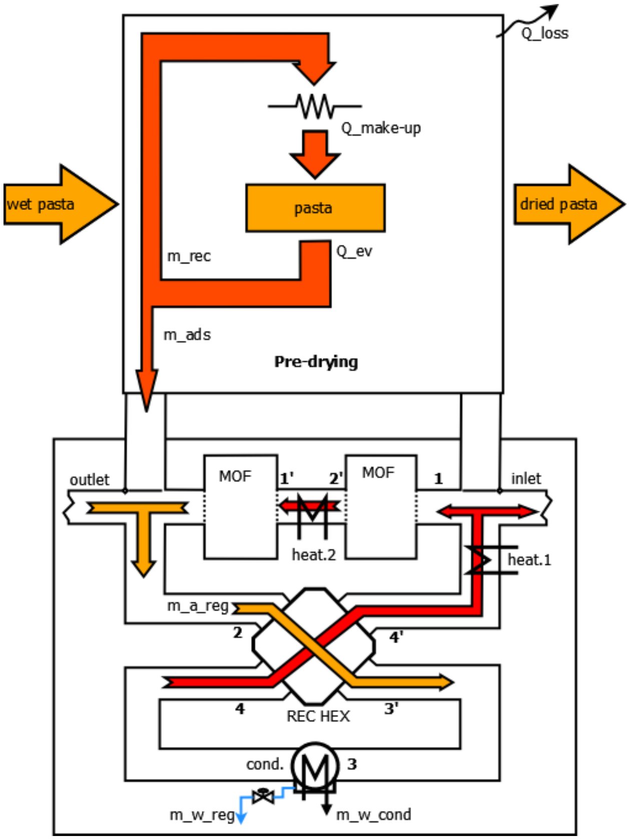

Figure 11: Schematic of the regeneration process with intermediate reheating.

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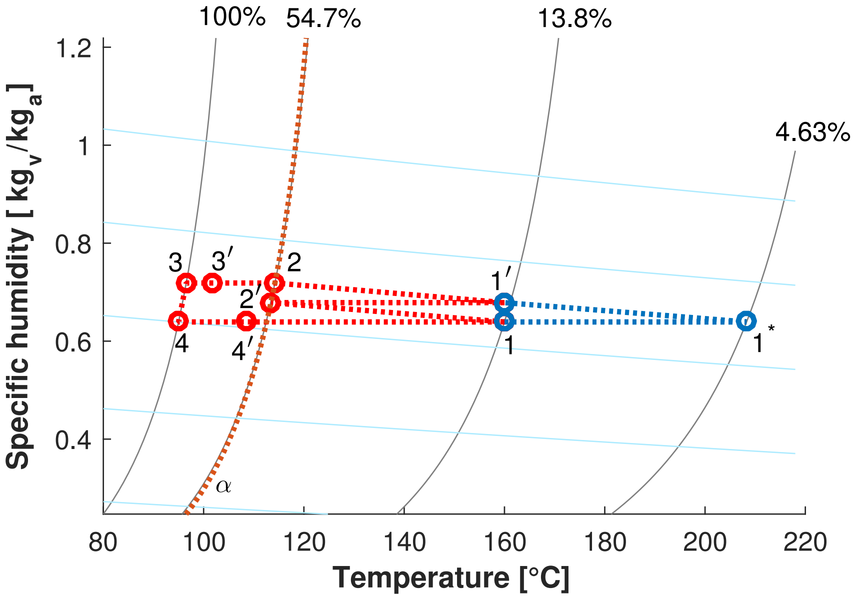

Figure 12: Regeneration process with intermediate reheating (red lines) and without (blue lines); total humid air pressure $p_{tot} = 168.2\,\mathrm{kPa}$.

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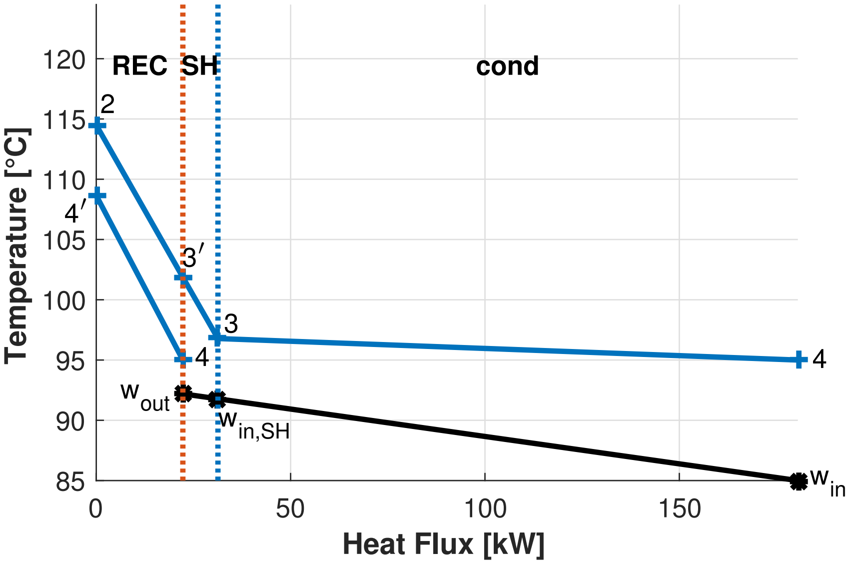

Figure 13: Heat exchange diagram for a regeneration process with intermediate reheating: recuperator and condenser.

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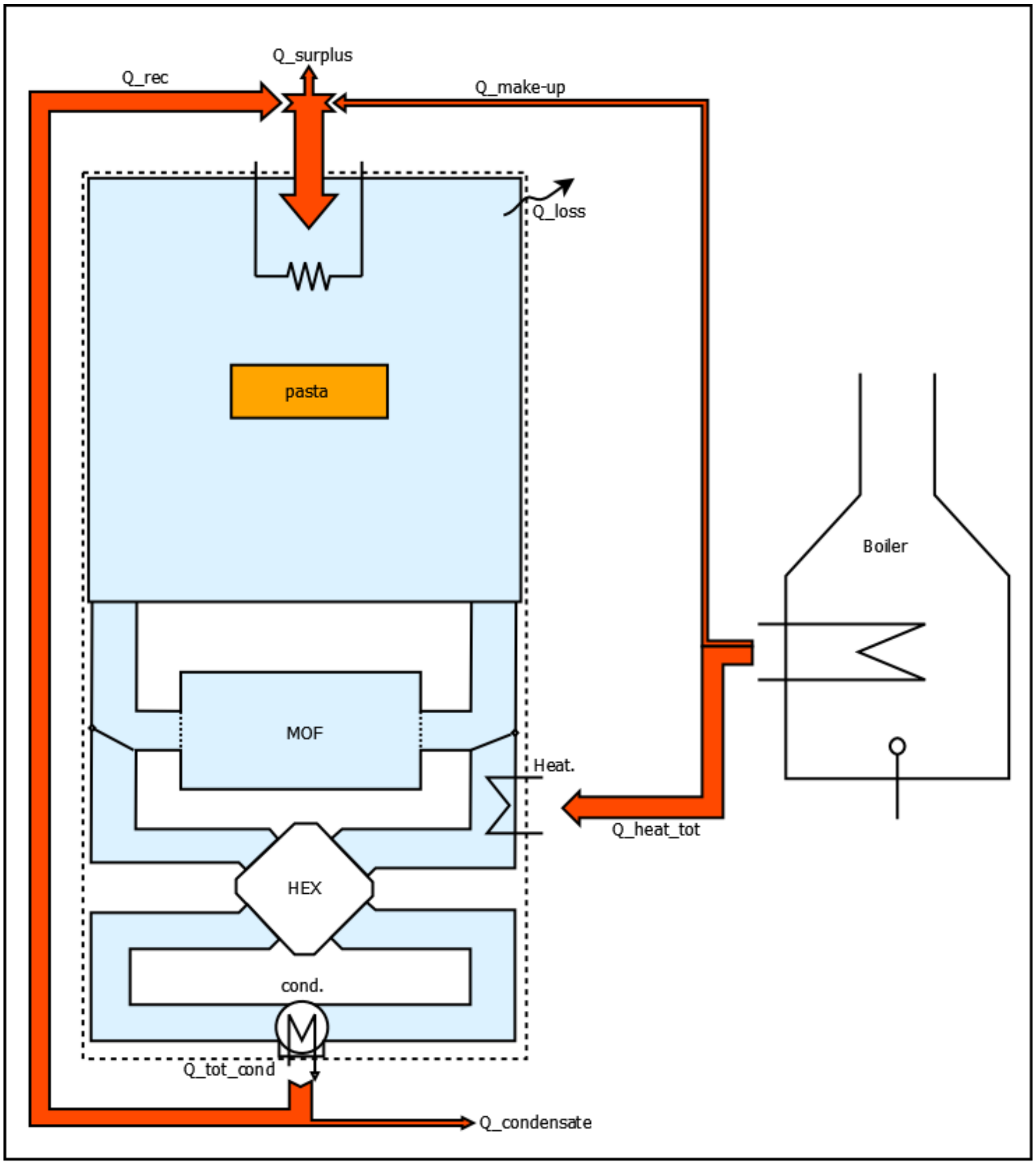

Figure 14: Schematic of energy flows in a real case.

Sara Bellocchi, Giuseppe Leo Guizzi, Michele Manno, Marzia Pentimalli, Marco Salvatori, Alessandro Zaccagnini, Adsorbent materials for low-grade waste heat recovery: Application to industrial pasta drying processes, Energy 140 (2017) 729-745, https://doi.org/10.1016/j.energy.2017.09.008.

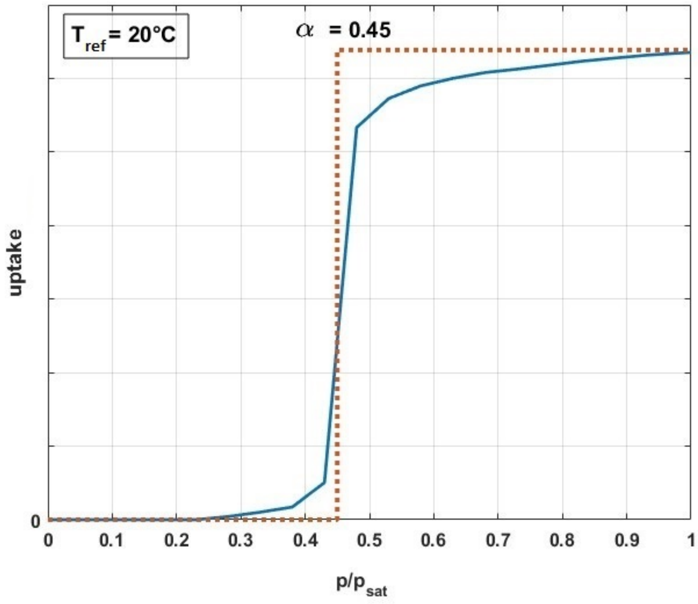

Figure 15: Adsorption isotherms at 20 °C for a real MOF (blue curve) and the theoretical approximation used in this study (red dotted curve).

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