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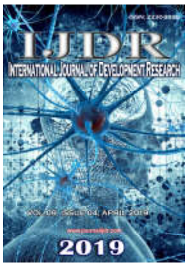

RESEARCH ARTICLE OPEN ACCESS

IMPROVING HEAT FLOW RATE AND CONDENSATE EFFICIENCY AFTER DRYINGBY A MASS AND ENERGY RE-USAGE TECHNIQUE

***Anita Kovac Kralj**

Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova 17, Maribor, Slovenia

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ABSTRACT

The drying process is of great importance to the food industry. One of the best techniquesfor food drying is re-using mass and energy of air outlets from dryers. Mass and energy re-usage of waste can reduce carbon emissions and the use of fossil fuelsin industrial food processes. For this purpose, a mass and energy re-usage technique has been developed in a system of heat flow rate and condensate recovery from air outlets after drying. The special benefits of this technique are

- Improvements in energy efficiency
- Inclusion of condensate recovery
- Calculation of the maximal total recovery heat flow rate using spaghetti design
- Modification of heating evaporators.

The aim of this study was to measure the masses and energies, as available heat flow rate and condensates, in re-usage of air outlets after drying. This technique is based on the use of pinch analysis principles. Mass and energy re-usage of air outlets after drying can significantly reduce energy costswithin the food industry. Besides heat flow rate recovery improvement benefits, condensate recovery is one of the main advantages of the proposed modifications. Our investigation was carried out to evaluate mass and energy re-usage of air outlets from dryinginthe sugar industry and found increases in efficiencyover existing production of 60%.

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INTRODUCTION

A performance evaluation of any industrial dryer regarding energy consumption and product quality should be assessed in order to check its present status and to suggest more efficient drying and energy operation, including wastewater and condensate recovery. Tumambing and Driscoll (1991) modelled the performance of fluidised bed drying of paddy and found experimentally that the drying rate of paddy was affected by drying air temperature and bed thickness [1]. Modelling, simulation and experimental studies on fluidised bed paddy drying have also been reported by Prachayawarakorn et al. [2] and Prachayawarakorn et al. [3]. The cross-section area at the point of velocity measurement was measured and the volume of air was calculated usinga continuity equation by Sarker et al. [4]. The air velocity of the dryer’s bed was calculated using the same equation.

The initial moisture contents of paddy during harvest varied between 28 and 37% dry basis. There are many methods for preserving agricultural products, including pasteurising, cooling, atmosphere control, use of chemicals, applications of beta and gamma rays, and drying [5]. Drying of agricultural products has a number of advantages, including shelf life extension, quality improvement, and loss reduction. Moreover, after water removal, the final weight is much reduced, which in turn reduces transportation costs [6]. Research and development efforts to improve drying processes around the world show analmost exponential growth over the past three decades [7]. From ancient times, the drying of agricultural products under solar radiation has been a common practice. Generally, the high energy consumption required for water evaporation during the drying operation is a real concern [8]. Industrial drying aims at minimum energy consumption for maximum drying efficiency. Therefore, solar drying is an appropriate choice, which not only offers low cost drying but also decreases pollution caused by fossil fuel usage [9]. Paddy drying is beset by serious problems in all paddy-producing countries, especially in humid tropical climates, as it is the

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****Corresponding author:* Anita Kovac Kralj,**
Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova 17, Maribor, Slovenia

most critical operation after harvesting the rice crop. Delay in drying, incomplete drying or ineffective drying will reduce grain quality and enhance postharvest losses. In tropical countries, the paddy is usually harvested at high moisture content between 20% and 25% wet bases [10, 11]. Although new methods such as combined microwave or infrared–hot air drying [12, 13], super-heated steam drying [14] and spouted bed drying [15, 16] have been reported as efficient drying methods for quality rice, their uses for industrial purposes are still limited. A chemical heat pump (CHP) is proposed as one of the potentially significant technologies for effective energy utilisation during drying. Ogura and Mujumdar [17] studied the CHP and proposed a chemical heat pump dryer (CHPD) system for ecologically - friendly and effective utilisation of thermal energy while drying. CHPs are systems that use a reversible chemical reaction for changing the levels of the thermal energies stored by chemical substances [18]. These chemical substances play an important role in absorbing and releasing heat [19]. The advantages of thermo-chemical energy storage, such as high storage capacity, long term storage of both reactants and products and lowering heat loss, suggest that CHP could be a viable option for energy upgrading of low temperature heat flow rate, as well as storage [20].

In the literature on sugar cane harvesting, several studies have attempted to combine yield estimation with an optimisation model or a heuristic algorithm for optimising sugar cane cultivation and harvest scheduling [21, 22]. The spatial variation of cane yield is known and is found to be highly effective for harvest productivity [23]. In an attempt to explain cane yield variation, Lawes et al. employed two multivariate techniques, the 3-way mixture method of clustering and 3-mode principle component analysis, to identify meaningful relationships between farms that performed similarly for cane yield, and Commercial cane sugar (CCS) for whole mill productivity improvement [24]. Prakashet al. [25] presented findings on annual performance, environomical analysis, energy analysis and exergy analysis of a modified greenhouse dryer (MGD) operating under active mode (AM) and passive mode (PM). Daghigh and Shafieian [26] constructed and experimentally evaluated a heat-pipe evacuated tube solar dryer with a heat recovery system in which water was used as working and recovery fluid in the solar and dryer loops, and air was used as an intermediate fluid in the dryer section. The heat recovery system was used to enhance the overall efficiency of the system and to make maximum use of the solar energy intake of the dryer. Yang et al. [27] tested a closed-loop heat pump drying system with a simultaneous control strategy, which is proposed to improve the precision of superheating and drying temperature. Stability of the drying temperature guarantees the quality of the drying material. On this premise, superheat should be accurate and stable enough to improve energy usage. Pinch analysis, along with other principles of process integration, has become established as one of the more important tools for analysing and optimising the energy systems of process plants. The principles of pinch analysis were formulated by Linnhoff and co-workers [28]. The second edition (1994) [29], included heat exchanger networks (HEN) syntheses, heat recovery targeting, and selecting multiple utilities. The second edition [29] was elaborated on by Kemp [30] in a book that includes optimisation of energy use, and energy saving using practical applications. Forty years of heat integration by using pinch analysis and mathematical programming has been summarizedby Klemeš and Kravanja [31]. Wang and Smith researched the minimisation of wastewater within process industries [32]. Their targets are the first set that maximise water re-use. This approach allows individual process constraints relating to minimum mass transfer driving force, fouling, corrosion limitations, etc. Waste reduction through source reduction and on-site recycling using techniques of process integration is an important aspect of pollution prevention [33]. In this study, an algorithmic procedure is presented for reducing waste generation through maximising on-site reuse/recycling. The methodology proposed is based on pinch principles and establishes a minimum waste generation target prior to detailed network design. Recovery of the waste heat within condensate and reuse of water may provide avenues for decreasing net energy and water usage at processing facilities. However, new processing methods are needed to create demand for condensate waste heat [34, 35]. New methodsfor reducing energy use have been developed overthe past several years. These methodsare designedforuse withinindustry and include multi-criteria optimisation [36], steam generation [37], and wastewater collection for steam generation [38]. The energy saving measures also result in lower CO_2 emissions [39]. The energy can be saved within internal [40] or between processes [41] including the estimating of maximal energy recovery [42]. This study presents the estimating mass and energy re-usages of air outlets after drying, including modifications to heating evaporators using collected condensate.

Mass and energy re-usage techniques

The aim of this study was to investigate heat flow rate and condensate recovery improvement opportunities within food plants. The mass and energy re-usage of air outlets after drying indicate major potential for improvement within the following drying systems:

1. Air outlet heat flow rate recovery
2. Condensate recovery

The technique based on pinch analysis research could improve the efficiency of process heating within food plants. Mass and energyas heat flow rates and condensates, and re-usage of air outlets after the dryer, can significantly improve energy and mass effectswithin the food industry. Besides heat flow rate recovery improvement benefits, condensate recovery is one of the main advantages of the proposed modifications. The goal of the mass and energy re-usage technique is to improve the maximal available heat flow rate and condensate. The estimated analysis includes the waste of the outlet flow rate within the process. This technique is very useful regarding energy recovery without changing the basic process operation and reusing flow rate and condensate, therefore reducing energy and mass losses. This technique includes modifications to heating evaporators using waste heat flow rate and collected condensate. The mass and energy re-usage technique includes only those streams that do not change basic operations. Within the food industry,many evaporators operate for heating lower temperature differences using low-pressure steam. The low-pressure steam can be replaced by heat flow rate from the air outlet after drying.

The mass and energy re-usage problemcan be easily solvedby using two steps, without mathematical programming, for trivial problems, or complex for nontrivial problems with mathematical programming using mixed integer nonlinear programming (MINLP; [43]) algorithms.

The first step of this technique is to analyse existing heat flow rates and inlet/outlet temperatures of all thecold streams through theevaporators, which can be heated by using air outlets from the dryers. The process cold streams of the evaporators can be displayed by using the grand composite curve (GCC, [29]; Fig. 1) with minimal temperature differences.

The second step is analysingthe total air heat flow rate from the dryer. Thisisdisplayed as a linelocated above the GCC of the cold streams of the evaporators (Fig. 2). The total air heat flow is not completely useable.The useable air heat flow (Q_{air})depends on the lowest outlet temperature ($T_{cond,out,L}$, Fig. 1). The lowest output temperature after air cooling can be determined graphically where the air line crosses the GCC curve. The useable air heat flow (Q_{air}) could be shared between thevapourising (Q_{vap}) and condensing (Q_{cond}) parts (Eq. 1).

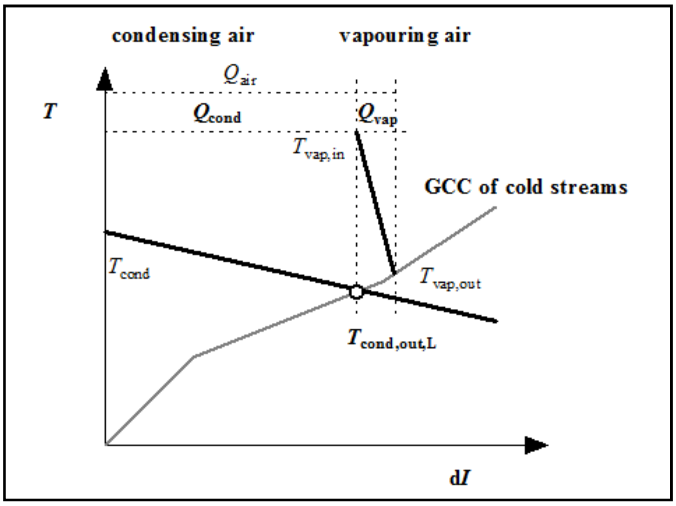

Figure 1. Diagram of mass and energy re-usage technique

The condensing and vapour air heat flow rate can be split into smaller parts depending on the number of individual evaporators (N_{ev}, Eqs. 2,3). The air outlet is analysedexactly, so that the vapour temperatures ($T_{vap,in}$,$T_{vap,out}$)can be determined, along with the initialcondensing temperature (T_{cond}), output temperature ($T_{cond,out}$, Eq. 4), and the fraction of condensing (f_{cond}, Eq. 5), by using linear function:

$$Q_{air}=Q_{vap}+Q_{cond} \quad \text{.......................................}(1)$$

$$Q_{cond}=\sum^{N_{ev}}Q_{cond,i} \quad \text{.............................}(2)$$

$$Q_{vap}=\sum^{N_{ev}}Q_{vap,i} \quad \text{......................}(3)$$

$$T_{cond,\ out,i}=a_T\cdot Q_{cond,i}+b_T \quad i=1,\ldots N_{ev} \quad \text{............................}(4)$$

$$f_{cond,i}=a_f\cdot T_{cond,out,i}+b_f \quad i=1,\ldots N_{ev} \quad \text{............................}(5)$$

The condensing part of air heat flow (Q_{cond}) can be presented by using one line (Fig. 1) or with more (Fig. 2) as the spaghetti design [44], which uses split streams. Spaghetti design allows greaterrecovery of heat flow ($dQ_{cond,sp}$) by 3.8%, which can be easily estimated without physical meaning using Equation 6. The recovery heat flow ratecan be determined by using the temperature difference of the spaghetti step (dT_{sp}; by using unit $^{o}C^{2}$), the condensing part of the heat flow rate (Q_{cond}), the starting condensing temperature (T_{cond}), and the lowest output temperature of the air stream ($T_{cond,out,L}$; Eq 6., Fig. 2):

$$dQ_{cond,sp}=[dT_{sp}\cdot Q_{cond}]\ /\ [T_{cond}-T_{cond,out,L}]^2 \quad \text{..........................}(6)$$

The maximal total recovery heat flow rate (Q_{rec}) can be evaluated using Equation 7:

$$Q_{rec}=Q_{vap}+Q_{cond}+dQ_{cond,sp} \quad \text{..........................}(7)$$

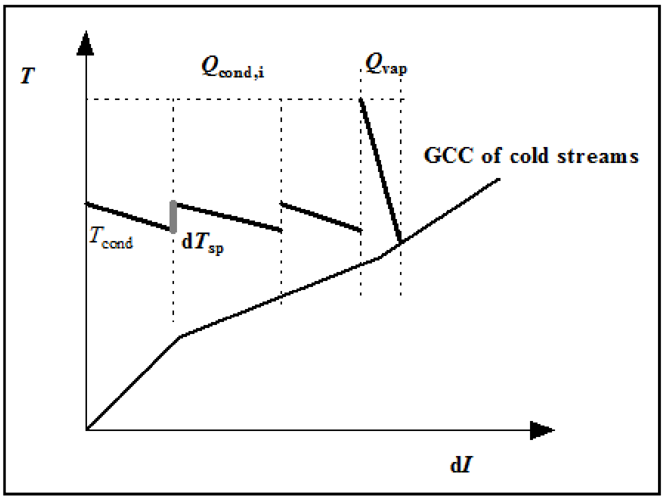

Figure 2. Diagram of the mass and energy re-usage technique using the spaghetti design

Distribution of the air stream from the dryer is presented in Figure 3; firstly, it is distributed by using vapour, and then the condensing parts of the heat flow. All streams after air cooling can be connectedwithin a condenser, including the non-active stream (Q_{rest}). Within the condenser, condensate can be collected for further use regarding utility preparation. The vapour stream then exits into the atmosphere (Fig. 3).

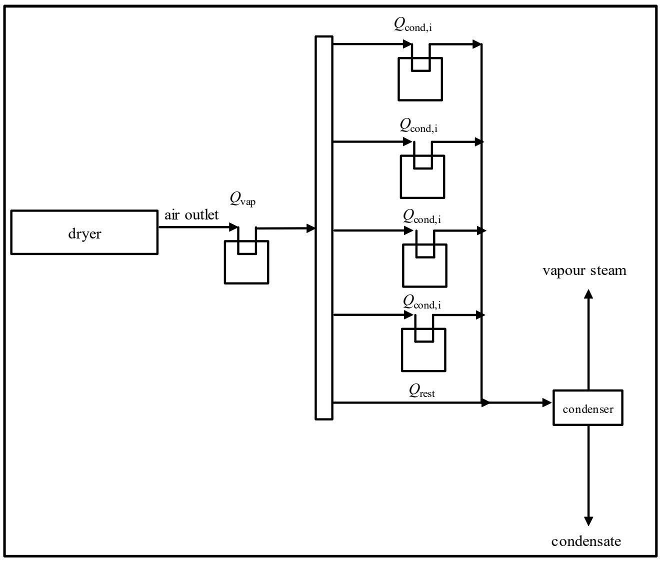

Figure 3.

Appropriate evaporators can be selected by including these requirements:

The temperature differences between the vapour and condensing air streams and the individual cold streams of the evaporator must be greater than or equal to 7°C (Eqs. 8, 9, 10, 11)

$$T_{vap,in,i} \geq T_{ev,out,i} \quad i = 1, \ldots N_{ev} \quad \ldots\ldots\ldots\ldots(8)$$

$$T_{vap,out,i} \geq T_{ev,in,i} \quad i = 1, \ldots N_{ev} \quad \ldots\ldots\ldots\ldots(9)$$

$$T_{cond,in,i} \geq T_{ev,out,i} \quad i = 1, \ldots N_{ev} \quad \ldots\ldots\ldots\ldots(10)$$

$$T_{cond,out,i} \geq T_{ev,in,i} \quad i = 1, \ldots N_{ev} \quad \ldots\ldots\ldots\ldots(11)$$

The mathematical model includes equations to calculate the vapour and condensing parts of the heat flow rate by using temperature differences and the heat capacity rates of individual evaporator cold streams ($CF_{ev,i}$, Eqs. 12, 13):

$$Q_{vap,i} = [T_{ev,out,i} - T_{ev,in,i,}] \cdot CF_{ev,i} = Q_{ev,i} \quad i = 1, \ldots N_{ev} \quad \ldots\ldots\ldots\ldots(12)$$

$$Q_{cond,i} = [T_{ev,out,i} - T_{ev,in,i,}] \cdot CF_{ev,i} = Q_{ev,i} \quad i = 1, \ldots N_{ev} \quad \ldots\ldots\ldots\ldots(13)$$

The vapour and condensing parts of the heat flow rate can be calculated using temperature differences and the heat capacity rates of the air streams (CF_{vap},$CF_{cond,i}$, Eqs. 14, 15):

$$Q_{vap,i} = [T_{vap,in,i} - T_{vap,out,i,}] \cdot CF_{vap,i} \quad i = 1, \ldots N_{ev} \quad \ldots\ldots\ldots(14)$$

$$Q_{cond,i} = [T_{cond,in,i} - T_{cond,out,i,}] \cdot CF_{cond,i} \quad i = 1, \ldots N_{ev} \quad \ldots\ldots\ldots\ldots(15)$$

The total selected evaporator heat flows (Q_{ev}) can be heated using an air stream, by using the same recovery air heat flow rate (Q_{rec}):

$$\sum_{1}^{N_{ev}} Q_{ev,i} \leq Q_{rec} \quad \ldots\ldots\ldots\ldots(16)$$

This mathematical model can be solved very easily for trivial problemsusing Equations 1 to 17; for serious problems it can be used for mixed integer nonlinear programming (MINLP; [43]) algorithms using Equations 1 to 22.The binary parameter, y_i, denotes the selection between the existing evaporators (N_{ev}; Eq. 18). The objective function (OBF; Eqs. 17) of the MINLP model is maximised for additional profit. The additional cost includes the cost of additional piping systems ($C_{p,i}$)and condenser (C_{con}). The additional income accounting for additional savings of steam ($In_{s,i}$)because the low–pressure steam would be replaced with anair stream from the dryer is calculated using equation 17:

$$OBF = \sum_{Nev} [((Q_{vap,i} + Q_{cond,i}) \cdot In_{s,I} \cdot y_i) - (C_{p,i} \cdot y_i + C_{con})] \quad \ldots\ldots\ldots\ldots(17)$$

$$\sum^{N_{ev}} y_i \leq N_{ev} \quad \ldots\ldots\ldots\ldots(18)$$

Many constrained engineering and industrial optimisation problems can be modelled as mixed integer nonlinear programming (MINLP) problems [43]. The MINLP approach deals simultaneously with both continuous and discrete (as binary) variables [43]. While continuous variables are defined for the continuous optimisation of parameters (heat flow rate-Q), discrete 0–1 variables are used to express discrete decisions, i.e. usually the existence (1) or non-existence (0) of structural elements within the defined structure. As the discrete optimisations are carried out simultaneously, together with continuous optimisation, the MINLP approach additionally determines the optimal continuous parameters. The handling of binary (y_i= 0,1;i = 1, …N_{ev}) variables allows for the specifications of those constraints that are relevant for synthesising a practical flow-sheet structure, in our caseselectingbetween existing evaporators (N_{ev}).

In addition, the binary variables can be related to activating or deactivating continuous variables, inequalities or equations: for example, consider the conditions for the continuous variable*x,* in our case the heat flow rate (Eqs 19–22):

if$y = 1 \rightarrow L \leq x \leq U$,if$y = 0 \rightarrow L\ x = 0$,

which can be modelled through the constraint: $Low \cdot y \leq x \leq Up \cdot y$ where *Low* is the lowest value and *Up* is the highest value of the parameters.

$$Q_{cond,i} \geq Low_{cond,i} \cdot y_i \quad i = 1, \ldots N_{ev} (19)$$
$$Q_{cond,i} \leq Up_{cond,i} \cdot y_i \quad i = 1, \ldots N_{ev} \quad \ldots\ldots\ldots\ldots(20)$$
$$Q_{vap,i} \geq Low_{vap,i} \cdot y_i \quad i = 1, \ldots N_{ev} (21)$$
$$Q_{vap,i} \leq Up_{vap,i} \cdot y_i \quad i = 1, \ldots N_{ev} (22)$$

Case study

The mass and energy re-usage technique is a very simple method that was tested and solved without mathematical programming during existing sugar production, including 9 evaporators (N_{ev} =9; Table 1, Figure 4). The existing evaporators used low-pressure steam for heating, which could be replaced by heat flow from the dryer.

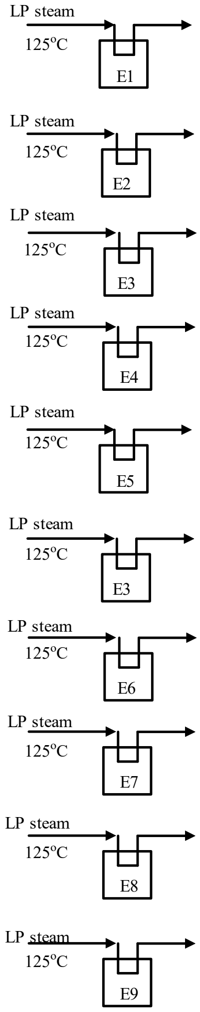

Figure 4. The existing evaporators within the sugar industry

The first stepin this technique represents the existing heat flow rates, and the inlet/outlet temperatures of all thecold streams through theevaporators, which can be heated using air from the dryer (Table 1). The process cold streams of the evaporators are introducedusing the grand composite curve (GCC; Fig. 5) with $\Delta_{min}T$= 7°C.

Table 1. Evaporators' cold streams

Streams	T_s/°C	T_t/°C	I/kW
E1	70.00	90.00	1293.0
E2	9.00	38.00	1546.0
E3	27.00	40.00	2484.0
E4	40.00	59.00	3925.0
E5	59.00	83.00	5369.0
E6	83.00	88.00	1063.0
E7	88.00	95.00	1409.0
E8	93.00	101.00	1639.0
E9	101.00	111.00	2083.0

The second step is to analysethe air outlet stream from the dryer. The air outlet temperature was 125°C. The air stream included 36,300kg/h of water steam and 41,350kg/h of gases (O_2,N_2,CO_2). The total air heat flow rate from the dryerwas 20,400kW (if the air stream was cooled to 67°C). The lowest output temperature ($T_{cond,out,L}$, Fig. 5) after the cooling by the air stream, 79°C, was determined graphically from Figure 5.
The usableair heat flow rate (Q_{air}) was 14,100kW, which was shared with the vapour (Q_{vap}=1,100kW)and condensing (Q_{cond}=13,000kW) partsand located above the GCC of cold streams of the evaporators (Fig. 5). The condensing heat flow rate ($Q_{cond,i}$) is split into smaller parts based on the number of individual evaporators (N_{ev}). The vapour heat flow rate was too small to split. The inlet and outlet temperatures of the vapour air streams ($T_{vap,in}$,$T_{vap,out}$) were 125°C and 90°C. The initialcondensing temperature (T_{cond}) was 90°C. The output temperature ($T_{cond,out}$, Eq. 23), fraction of condensing (f_{cond}, Eq. 24) and condensing heat flow rate (in kW; Eq. 25) can be calculated using a linear function:

$$T_{cond,\ out,i} = -\,0.0009\cdot Q_{cond,i} + 89.16 \quad i = 1, \ldots N_{ev} \qquad \ldots\ldots\ldots\ldots..(23)$$

$$f_{cond,i} = -\,0.0258\cdot T_{cond,out,i} + 2.306 \quad i = 1, \ldots N_{ev} \qquad \ldots\ldots\ldots\ldots.(24)$$

$$Q_{cond,i} = 40395\cdot f_{cond,i} - 37.6 \quad i = 1, \ldots N_{ev} \qquad \ldots\ldots\ldots\ldots\ldots.(25)$$

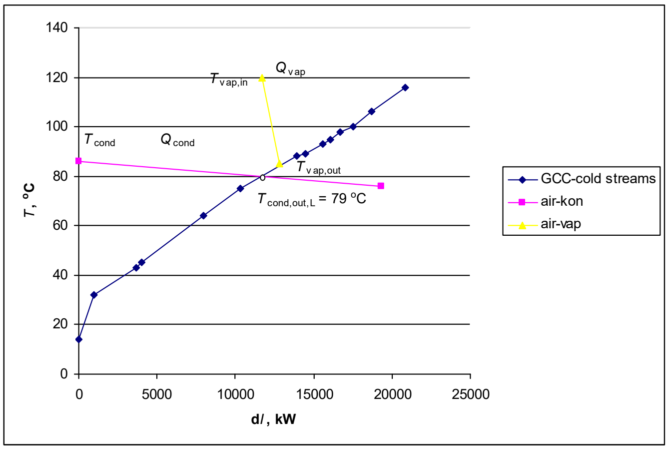

Figure 5. Diagram of mass and energy re-usage techniques for the existing evaporators

The condensing part of the air heat flow rate (Q_{cond}) is presented by using more linesinthe spaghetti design, which allows greater heat flow recovery ($dQ_{cond,sp}$) by 3.8%. This can be determined by using the temperature differences of spaghetti step (dT_{sp}; by using unit $^{o}C^2$), the condensing part of the heat flow rate (Q_{cond}), the initial condensing temperature (T_{cond}), and the lowest output temperature of the air stream ($T_{cond,out,L}$; Eq 26., Fig. 6):

$$dQ_{cond,sp} = [dT_{sp}\cdot Q_{cond}]\,/\,[T_{cond} - T_{cond,out,L}]^2 = [5\cdot 13000]/\,[90-79]^2 = 500\text{kW} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(26)$$

The maximal total recovery heat flow rate (Q_{rec}) can be evaluated using Equation 27:

$$Q_{rec} = Q_{vap} + Q_{cond} + dQ_{cond,sp} = 1.100 + 13000 + 500 = 14.600\text{kW} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(27)$$

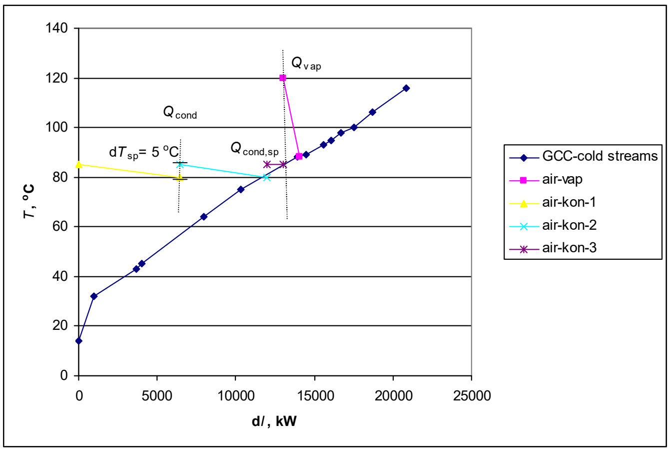

Figure 6. Diagram of the mass and energy re-usage technique using the spaghetti design for existing evaporators

Appropriate evaporators can be selected by including the temperature requirements. The temperature differences between the vapour and condensing air streams and individual cold streams of the evaporator must be greater than or equal to 7°C (Eqs. 8, 9, 10, 11); therefore, evaporators should be selected from choices E2 to E6 (Table 1). E6 can be heated with only the vapour part of the air heat flow because of the high required temperatures from this evaporator. E2–E5 can be heated with the condensing part of air from the heat flow. Existing evaporators E1 and E7–E9 remain unchanged. Distribution of the air stream from the dryer is shown in Figure 7.

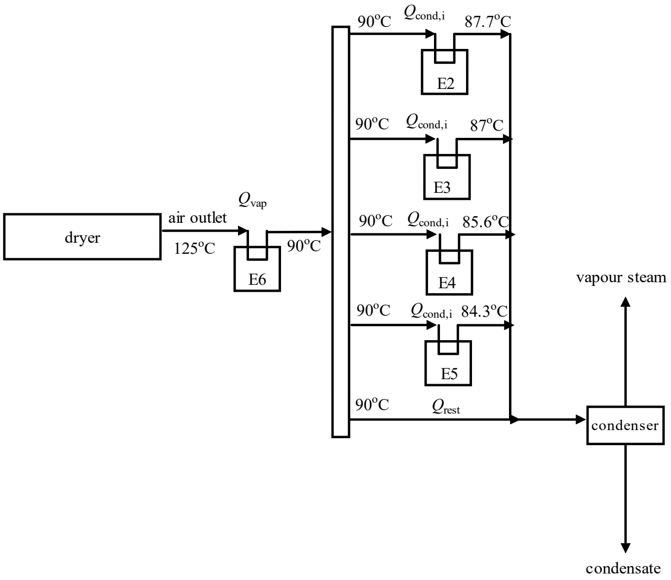

Figure 7. Distribution of air stream from the dryer to the existing evaporators

Air is first distributed by using vapour which can heat the evaporator, then the condensing parts of the heat flow rate. All streams after air cooling are connected, including the non-active stream (Q_{rest}), into the condenser, where condensate for further use is collected for utility preparation. The vapour stream is vented into the atmosphere (Fig. 7). This mathematical model could be solved very easily without the MINLP model. The additional cost includes the cost of additional piping systems ($C_{p,i}$= 4,000 EUR/a) and the condenser (C_{con}=80,000EUR/a) 100,000EUR/a (Eq. 28.).The additional income accounts for the savings of steam ($In_{s,i}$=60EUR/(kW·a) saved 876,000 EUR/a.Replacing the low-pressure steam would generate a profit of 756,000EUR/a.

$$OBF = \sum_{Nev}[((Q_{vap,i} + Q_{cond,i})\cdot In_{s,I}\cdot y_i) - (C_{p,i}\cdot y_i + C_{con})]$$

$$=[((14{,}600)\cdot 60) - (4000\cdot 5 + 100{,}000)] = 756{,}000 \;\ldots\ldots\ldots\ldots(28)$$

Conclusions

A large amount of re-usable thermal energy and condensatesfrom industrial processes is emitted into the environment every year as energy and mass wastes.Mass and energy re-usage techniques can be useful for increasing the efficiencies of conventional energy and mass systems.The re-usage of waste heat would have positive benefits for reducing the amount of resources consumed and waste and pollutants generated within industries. Waste-heat recovery techniques that are environmentally friendly and have technical and economic advantages should be assessed for possible contributions to the energy economy and to national economies. The mass and energy re-usage technique, as a simple method of using air heat flow from industrial dryers, is based on more efficient steam generation targets, using pinch analysis and/or MINLP. The mass and energy re-usage technique can be implementedby using two steps, easily without mathematical programming for trivial problems or complex with mathematical programming. This technique provides estimates of the maximal total recovery of mass and energy within industrial food production facilities by using spaghetti design. Implementing a smart heat recovery system for converting waste heat flow into useful energy can help achieve industrial cost savings.

This investigation of heat flow rate and condensate recovery demonstrates improvement opportunities within food plants. Mass and energy re-usage of air outlets after drying promises major potential for improvement within drying systems in:

- air outlet heat flow recovery
- condensate recovery
- modification of heating evaporators.

In the facility studied, modification of the existing evaporators E2–E6, including a minor retrofit ofthe existing sugar refining processby replacing low-pressure steamwith air heat flow dryers,would allow additional profits of 756,000 EUR/a.

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