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# Evaluating the Trade-Off Between Energy Efficiency and Energy Saving in Spray Drying Operations

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**Anahtar Kelimeler**

*Püskürtmeli kurutucu*
*Enerji verimliliği*
*Enerji tasarrufu*
*Süt tozu*

***Graphical/Tabular Abstract (Grafik Özet)***

*In this study, the relation between energy recovery and energy efficiency for milk powder production in spray dryer was investigated. / Bu çalışmada sprey kurutucuda süt tozu üretimi için enerji geri kazanımı ve enerji verimliliği arasındaki ilişki incelenmiştir.*

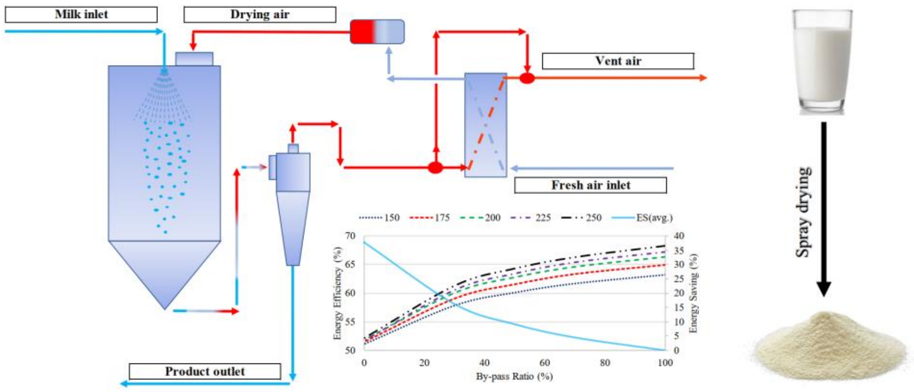


***Figure A:*** *Spray dryer system for milk powder production /* ***Şekil A:*** *Süt tozu üretimi için püskürtmeli kurutucu sistemi*

***Highlights (Önemli noktalar)***

- *Using energy recovery to reduce energy consumption in spray dryer / Püskürtmeli kurutucuda enerji tüketiminin azaltılması için enerji geri kazanımının kullanılması*
- *Analysis of factors affecting milk powder production in spray dryer / Püskürtmeli kurutucuda süt tozu üretimini etkileyen faktörlerin incelenmesi*
- *Examining the relation between energy saving and energy efficiency / Enerji tasarrufu ve enerji verimliliği arasındaki ilişkinin incelenmesi*

***Aim (Amaç):*** *This study aims to explore the integration of heat recovery systems with proportional by-pass application in spray drying processes, examining their applicability for increasing energy efficiency. / Bu çalışmanın amacı, püskürtmeli kurutma proseslerinde orantılı by-pass uygulaması ile ısı geri kazanım sistemlerinin entegrasyonunu araştırarak enerji verimliliğini artırmada uygulanabilirliğini incelemektir.*

***Originality (Özgünlük):*** *In spray dryers, three key parameters significantly impact system performance: drying air flow rate, drying air temperature, and product flow rate. This study simplified the three-variable equation by reducing two variables (drying air flow rate and temperature) to a linear constant coefficient. This approach facilitated the simultaneous examination of all three input parameters and allowed for an understanding of their individual effects on system efficiency. / Püskürtmeli kurutucularda, üç temel parametre sistem performansını önemli ölçüde etkiler: kurutma hava debisi, kurutma havası sıcaklığı ve ürün debisi. Bu çalışma, iki değişkeni (kurutma hava debisi ve sıcaklık) doğrusal bir sabit katsayıya indirgeyerek üç değişkenli denklemi basitleştirdi. Bu yaklaşım, üç girdi parametresinin eş zamanlı olarak incelenmesini kolaylaştırdı ve bunların sistem verimliliği üzerindeki bireysel etkilerinin anlaşılmasına olanak sağladı.*

***Results (Bulgular):*** *At a 30% bypass ratio, energy efficiency and energy savings were found to be approximately 60% and 16%, respectively. / %30 bypass oranında enerji verimliliği ve enerji tasarrufu sırasıyla yaklaşık %60 ve %16 bulunmuştur.*

***Conclusion (Sonuç):*** *The optimal bypass ratio was found 30%. At this ratio, energy efficiency decreased by 5%, while energy savings increased by approximately 16%. / Optimum bypass oranı %30 olarak bulundu. Bu oranda enerji verimliliği %5 azalırken, enerji tasarrufu yaklaşık %16 arttı.*

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**Abstract**

In this study, modeling simulations were employed to analyze the effects of inlet drying air flow rate and temperature, product flow rate, and heat recovery ratio in a spray dryer. The energy efficiency, energy savings, and final product outlet temperature were investigated. As the heat recovery ratio increased, total energy savings improved, though energy efficiency declined at a slower rate compared to energy savings. The modelling study was conducted with five different bypass ratios: 100%, 70%, 50%, 30%, and 0%, indicating that the optimal bypass ratio was 30%. At this ratio, energy efficiency decreased by 5%, while energy savings increased by approximately 16%. Additionally, at lower bypass ratios, the product outlet temperature rose significantly. To maintain product quality, it was found that the maximum acceptable temperature of 60°C could be achieved at bypass ratios of 30% or higher.

# Sprey Kurutma İşlemlerinde Enerji Verimliliği ile Enerji Tasarrufu Arasındaki Dengenin Değerlendirilmesi

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**Öz**

Bu çalışmada, bir sprey kurutucuda giriş kurutma havası debisi ve sıcaklığı, ürün debisi ve ısı geri kazanım oranının etkilerini analiz etmek için modelleme simülasyonları kullanılmıştır. Enerji verimliliği, enerji tasarrufları ve son ürün çıkış sıcaklığı incelenmiştir. Isı geri kazanım oranı arttıkça, toplam enerji tasarrufu iyileşmiş, ancak enerji verimliliği enerji tasarruflarına kıyasla daha yavaş bir oranda düşmüştür. Beş farklı by-pass oranıyla (100%, 70%, 50%, 30% ve 0%) gerçekleştirilen modelleme çalışması, optimum by-pass oranının %30 olduğunu göstermiştir. Bu oranda enerji verimliliği %5 azalırken, enerji tasarrufu yaklaşık %16 artmıştır. Ayrıca, daha düşük by-pass oranlarında ürün çıkış sıcaklığı önemli ölçüde artmıştır. Ürün kalitesini korumak için, %30 veya daha yüksek by-pass oranlarında kabul edilebilir maksimum sıcaklık olan 60°C'ye ulaşılabileceği bulunmuştur.

## 1. INTRODUCTION (GİRİŞ)

Spray drying is a widely used in diverse fields, where it serves as an efficient and effective method for manufacturing dry powders or granules from liquids or slurries. This method transforms a liquid or slurry into a fine spray pattern, quickly dried with hot air, resulting in a dry powder or granule with a highly uniform particle size and moisture content. Although spray drying is a key process in various industries due to its efficiency and effectiveness, it is also recognized as an energy-intensive process. The high thermal energy requirement due to producing large volumes of heated air have led to research and development efforts to increase energy efficiency and reduce energy consumption. Several systems have been proposed to reduce energy consumption in spray drying, including exhaust air recovery, exhaust air recirculation, and the combination of a spray dryer with a fluid bed dryer. [1]. One of the ways to reduce energy consumption in drying systems is energy recovery. There were studies in the literature on the use of energy recovery in dryers. However, there were few studies on heating fresh air by utilizing the energy of waste heat they [1–5] performed model simulations to evaluate energy recovery potential of reusing of exhaust air in spray drying process. The drying process of alumina-based ceramic composite slurry has been assessed. The effects of temperatures and

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flow rates of the inlet drying air and product feed are investigated on both energy saving and efficiency for different exhaust air recirculation ratio.

Patel and Bade (2022) achieved a 26% improvement in energy savings and an 83% increase in energy efficiency for a spray dryer utilizing a 70% exhaust air recirculation ratio [6]. Oliveira et al. (2021) used spray drying for lipid microencapsulation process. Simulated and experimental results were compared, and the difference was about 9%. The decreases in the thermal load for drying air were 18% and 32% when direct heat recovery (DHR) and indirect heat recovery (IDHR)were used, respectively. IDHR, the energy was extracted from the waste heat and given to the fresh air with the heat exchanger. IDHR, after the waste air passed through the humidifier, it was given to the drying cabinet [7]. Patel and Bade (2020) compared the energy recovery configurations of a spray dryer with both literature data and a base case using pinch analysis. The base case was defined as a spray dryer without any heat recovery (HR), while the other configurations included an IDHR system (case 1) and a hybrid heat recovery (HHR) system with 80% exhaust air recirculation (case 2). Dryer efficiencies of the base case, case 1 and 2 were 21%, 41% and 68%, respectively. Energy savings of the case 1 and 2 according to the base case were 57% and 75%, respectively. Recirculation ratios of 0.2, 0.6, and 0.8 resulted in enhanced energy saving potential of 63%, 70%, and 74%, respectively. For RR of 50% and 80%, the difference in the dryer's height from the base scenario was 17.2% and 45.86%, respectively. Thus, DHR must be considered during the design phase of the new spray dryer, particularly for larger recirculation ratios (over 50%) [8]. Camci (2020) theoretically investigated spray drying process assisted with solar powered renewable system. Photovoltaic panels and parabolic trough collectors were utilized for electricity and heat to the system. Energy efficiencies of the spray dryer, evaporator and overall were 64.24%, 86.56% and 75.01%, respectively, in the PTC-SP milk powder production system. The overall exergy efficiency of the system was 11.10% [9]. Julkland et al. (2015) examined the energy efficiency of a large-scale spray dryer combined with an exhaust HR system for drying dilute slurry. Both energy efficiency and savings were determined using a detailed mathematical model of the spray dryer. The highest energy savings of 52.4% resulted from the interplay between the adverse impact of the slurry feed rate and the beneficial effect of the drying air temperature. The highest energy efficiency of 43.3% was achieved at a high feed rate of the dilute slurry [2]. Golman and Julklang (2014) simulated exhaust gas HR from a spray dryer for drying of large amount of dilute slurry. Waste heat was utilized with an air-to-air heat exchanger, thus energy efficiency increased by 16% and energy saving was 50% [4]. Patel and Bade (2019) compared different HR system according to the environmental impact and energy saving potential. Spray dryer with HHR system at 80% recirculation ratio dryer efficiency was 66% and energy saving was 82800 kJ/hr. The energy efficiency of spray dryer without energy recovery configuration and with DHR system were 21% and 51%, respectively, at same recirculation ratio 80%. Reduction in heat load and dryer efficiency of HR system were 23.8% and 29% higher than that's of the DHR system [10]. Caglayan and Caliskan (2017) calculated the sustainability index of a spray dryer with a heat exchanger based on varying dead state temperatures between 0 and 20°C. At 0°C, the sustainability indexes of the spray dryer and the overall system were 1.351 and 1.308, respectively. The energy efficiency of the heat exchanger was 63.32%, while that of the overall system was 5.56%, indicating that the combination of the two was more effective [11].

Ai et al. (2016) proposed a HR system for a spray dryer aimed at reducing energy consumption in the drying of soy protein powder. A water loop was established between the exhaust air and fresh air to prevent bacterial growth during air recirculation. The drying air was preheated using a HR heat exchanger and a heat pump before entering the boiler. The total initial cost of the HR system was $501,000, accounting for 15% of the total initial investment. The payback period for the HR system was approximately 2.4 years, with an energy savings rate of 21% compared to the traditional system [12]. In another study, Walmsley et al. conducted a techno-economic optimization to determine the most effective heat exchanger for recovering heat from the exhaust air of a milk spray dryer. They concluded that a finned tube heat exchanger with 14 tube rows and a face velocity of 4 m/s was the best option. This configuration yielded an internal rate of return of 71% and a net present value of NZ$2.9 million [11]

Chen et al. (2022) investigated a desiccant wheel-assisted high-temperature heat pump (HTHP) technology for heating the inlet air of milk spray dryers up to 150 °C by utilizing HR from the dryer exhaust. Using a desiccant wheel assisted HTHP was reduced evaporator size about 50–60 % according to the HTHP. Using of desiccant wheels with heat pump were especially important for recovery exhaust air under diverse ambient conditions and high humidity [12]. Moejes et al. (2018) optimized and simulated closed loop spray drying system to decrease energy consumption for dairy industry. The offered technologies were a zeolite wheel, membrane contactor, and monodisperse droplet atomizer. Sensible and latent heats from dryer exhaust were used to preheat milk and the drying air. The energy usage significantly decreased from 8.4 to 4.9 MJ of heat per kg of milk powder by integrating the adsorber-regenerator system with the spray dryer and the prior milk concentration process [3]. Currently, producing skim milk powder used about 10 MJ of energy per kilogram of powder. Integrating reverse osmosis with membrane distillation, monodisperse droplet drying, and zeolites has the potential to decrease the energy needed for milk powder production to 4-5 MJ/kg. Other feasible combinations, however, would require more energy, approximately 5-7 MJ/kg of powder. [13]. The drying system should be run at low product feed rate, high recirculation ratio of exhaust air and high product concentration in order to ensure the maximum energy saving [5]

As understood from previous studies, one promising approach to increase the energy efficiency and reduce the energy consumption of a spray drying system is the integration of a HR system which is applied to the exhaust heat line to capture and reuse thermal energy that would otherwise be lost. By this application, the required thermal energy to produce hot air can significantly decrease, and energy efficiency can be increased. This not only improves the energy efficiency of the spray dryer but also reduces operational costs and the carbon footprint by minimizing energy waste and gas emissions. This study aims to explore the integration of HR systems with proportional by-pass application in spray drying processes, examining their applicability for increasing energy efficiency. Through a detailed heat and mass transfer analysis, the goal is to find the optimized by-pass ratio to achieve highest possible energy efficiency for various hot air temperatures, liquid feed flow rates, and hot air flow rates. In spray dryers, three key parameters significantly impact system performance: drying air flow rate, drying air temperature, and product flow rate. Although other parameters also influence efficiency, these three parameters play a decisive role. However, analyzing these three parameters simultaneously is like solving a three-variable equation, which is exceedingly challenging. In previous studies documented in the literature, these three input parameters were varied continuously while maintaining energy efficiency as constant. However, such studies failed to elucidate the mutual interactions or stepwise effects of these parameters on the system. To address this limitation and fill the gap in the literature, the present study simplified the three-variable equation by reducing two variables (drying air temperature and drying air flow rate) to a linear constant coefficient, thus enabling a more straightforward analysis. This reduction to a linear constant coefficient was performed based on a review of existing literature. Studies indicated that the ratio of drying air flow rate to drying air temperature consistently ranges between 13 and 15 [4,5]. At lower temperatures, this ratio started at approximately 13 and increased towards 15 as the temperature rises. In this study, the ratio was fixed as a constant linear coefficient in alignment with the literature, and subsequent analyses were conducted. This approach facilitated the simultaneous examination of all three input parameters and allowed for an understanding of their individual effects on system efficiency.

## 2. METHODOLOGY (METODOLOJİ)

Fresh air is heated in a heat exchanger and directed to the dryer. Atomizing air is utilized to remove water from the milk, which is sprayed from the top of the drying chamber. The frying air leaves the dryer at low temperature and high relative humidity. Solid agglomerates formed during the drying process are discharged from the lower part of the drying chamber along with the exhaust air. A cyclone separates the agglomerates from the exhaust drying air and sending them to the final product line. If necessary, the exhaust air can be further cleaned using a bag filter. When in recovery mode, the exhaust air heats fresh air in a cross-flow heat exchanger. However, due to the high relative humidity of the exhaust air, a portion of it is bypassed. Fresh air is preheated by passing through the heat recovery exchanger (HX2) and then heated to the desired temperature in additional main heat exchanger (HX1). This study investigates the impact of preheating fresh air with exhaust air using HR the specified conditions. The schematic diagram of the milk spray drying system, with and without HR, is illustrated in **Figure 1**.

Three parameters affecting the dryer's performance are drying air temperature, drying air flow rate, and product flow rate. A heat exchanger is placed on the exhaust side for HR. However, since the relative humidity of the exhaust air is at 50-60%, there is a risk of condensation in the exchanger when it meets fresh air. For this reason, some of the air is bypassed and given to the mixing chamber at the heat exchanger outlet. To prevent condensation in the heat exchanger, the drying air flow rate or temperature can be increased. However, these are assumed to be constant coefficient. The other alternative is to reduce the product flow rate, which will result in lower relative humidity in the drying air because less water will evaporate.

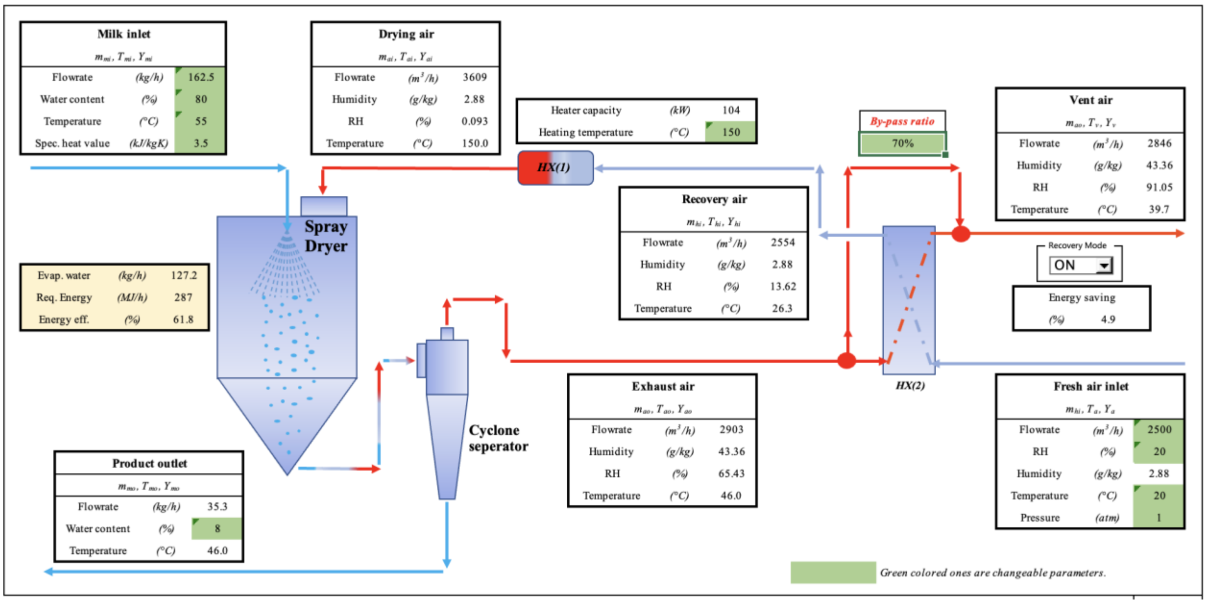



**Figure 1.** Schematic diagram of the milk spray drying with and without heat recovery (Isı geri kazanımlı ve ısı geri kazanımsız püskürtmeli süt kurutmanın şematik diyagramı)

The analysis procedure is as follows:

1. Calculations are performed so that the outlet air relative humidity (in HX2) would be 90%.
2. The $M_{da}/T_{da}$ ratio is accepted as a constant coefficient that varies linearly with temperature by referring to the literature (between 13 and 15) [4,5].
3. Analyses are performed for drying air temperatures of 150, 175, 200, 225 and 250 °C, respectively. The temperature range used in the literature is between 160-300 °C [4,5].
4. As stated in item 2, drying air mass flow rate is determined according to the $M_{da}/T_{da}$ ratio for each temperature.
5. With the fixed inputs determined because of items 2 and 3, only $M_p$ remains as a variable. Iterative analysis is performed to obtain the highest energy efficiency result for the values given for $M_p$.
6. The $M_p$ value is determined for the highest energy efficiency value and the $M_{da}/M_p$ ratio is calculated.
7. The product outlet temperature is determined according to heat and mass transfer analyses.

It is assumed that there is no loss in the system and the inlet energy is equal to the outlet energy.

$$Q_{in} = Q_{out} \tag{1}$$

The energy balances of the whole system are given Eqs. 1, 2, 3, 4, 5, 6, 7 and 8. Heat input to the spray drying system comes from milk feed, drying air, HX1 and HX2.

Milk feed

$$Q_{mi} = m_{mi}.\left(c_{p,solid} + x_{mi}.c_{p,liquid}\right).\left(T_{mi} - T_{ref}\right) \tag{2}$$

Air inlet

$$Q_{ai} = m_{ai}.\left[\left(c_{p,ai} + Y_{ai}.c_{p,vapour}\right).\left(T_{hi} - T_{ref}\right) + Y_{ai}.\lambda_{ref}\right] = m_{ai}.h_{ai} \tag{3}$$

Through first HX

$$Q_h = m_{ai}.\left(c_{p,ai} + Y_{ai}.c_{p,vapour}\right).\left(T_{ai} - T_{hi}\right) = m_{ai}\left(h_{ai} - h_{hi}\right) \tag{4}$$

Through second HX

$$Q_{rec} = m_{ao}.\left(c_{p,ao} + Y_{ao}.c_{p,vapour}\right).\left(T_{ao} - T_{ref}\right).\eta_{hx,2} = m_{ai}\left(h_{ao} - h_e\right)$$

Total

$$Q_{in} = Q_{mi} + Q_{ai} + Q_h - Q_{rec} \tag{5}$$

Heat output from the system occurs through solid product and exhaust air.

| | | |
|---|---|---|
| Solid product discharge (milk powder) | $Q_{mo} = m_{mo}.\left(c_{p,solid} + x_{mo}.c_{p,liquid}\right).\left(T_{mo} - T_{ref}\right)$ | (6) |
| Exhaust air | $Q_{ao} = m_{ao}.\left[\left(c_{p,ao} + Y_{ao}.c_{p,vapour}\right).\left(T_{ao} - T_{ref}\right) + Y_{ao}.\lambda_{ref}\right] = m_{ao}.h_{ao}$ | (7) |
| Total heat input | $Q_{out} = Q_{mo} + Q_{ao}$ | (8) |

The mass balances of the dryer are given in Eqs. 9, 10 and 11.

| | | |
|---|---|---|
| Dry solids | $m_{mi,d} = m_{mo,d}$ | (9) |
| Dry air | $m_{ai,d} = m_{ao,d}$ | (10) |
| Moisture | $m_{mi}.X_{mi} + m_{ai}.Y_{ai} = m_{mo}.X_{mo} + m_{ao}.Y_{ao}$ | (11) |

where Y is the humidity on dry basis kg $kg^{-1}$ and X is the mass fraction of water on dry basis kg $kg^{-1}$. Specific enthalpies of air streams of high humidity are calculated with Eq. 12. [14] .

$$h_i = c_{p,a}.\left(T_{i,a} - T_{ref}\right) + Y_{i,a}.\left[c_{p,liquid}.\left(T_{dew} - T_{ref}\right) + \lambda_{dew} + c_{p,v}.\left(T_{i,a} - T_{dew}\right)\right] \quad (12)$$

where $T_{dew}$ is the dew point temperature and $\lambda_{dew}$ is the latent heat of vaporization of water at $T_{dew}$ . The humidity of exhaust air is calculated by Eq. 13.

$$Y_{ao} = \frac{m_{mo,d}(X_{mi} - X_{mo}) + m_{ai,d}.Y_{ai}}{m_{ao,d}} \quad (13)$$

Energy efficiency can be defined as the ratio of the energy required for evaporation to the energy supplied to the dryer.

$$\eta_R = \frac{Q_{req}}{Q_{in}}.100 \rightarrow \% \quad (14)$$

$$Q_{req} = (X_{mi} - X_{mo}).m_{mi,d}.\lambda \quad (15)$$

When the inlet air is heated using HR, the amount of energy savings is calculated with Eq. 16.

$$energy\ saving = \frac{Q_{rec}}{Q_h} \quad (16)$$

The specific enthalpy of water vapor can be calculated as:

$$h_{v,i} = \lambda_{ref} + c_{p,v}.\left(T_i - T_{ref}\right) \quad (17)$$

$\lambda_{ref}$ is the latent heat of vaporization of water at $T_{ref}$ and, $c_{p,v}$ is the specific heat capacity of water vapor.

Mujumdar [14] were recommended using a more precise equation for calculating $h_{v,da}$ in the cases of high gas humidity, i.e. $Y_i > 0.05$ :

$$h_{v,i} = c_{p,l}.\left(T_{dew} - T_{ref}\right) + \lambda_{dew} + c_{p,v}.\left(T_i - T_{dew}\right) \quad (18)$$

Where $T_{dew}$ is the dew point temperature and $\lambda_{dew}$ is the latent heat of vaporization of water at $T_{dew}$.

The specific enthalpies of dry air, dry solids and water in state i can be calculated as:

$$h_{a,i} = c_{p,a}.\left(T_i - T_{ref}\right) \quad (19)$$

$$h_{m,i} = c_{p,m}.\left(T_i - T_{ref}\right)$$

$$h_{l,i} = c_{p,l}.\left(T_i - T_{ref}\right)$$

Specific enthalpy of drying air stream is defined by:

$$h_i = h_{a,i} + Y_i.h_{v,i} \quad (20)$$

$h_{a,i}$ and $h_{v,i}$ are the specific enthalpies of dry air and water vapor, respectively, and $Y_i$ is the humidity.

## 3. RESULTS AND DISCUSSION (BULGULAR VE TARTIŞMA)

A heat exchanger and a bypass system, which can be proportionally controlled are placed at the exhaust outlet to provide heat recovery. Drying system is examined at different bypass ratios. Heat recovery is not used when the bypass ratio (BR) is 100%. Drying air leaves the dryer at low temperature and high relative humidity, if this air encounters a cold surface, condensation occurs. To prevent exhaust air from condensing, some air is bypassed and mixed at the heat exchanger outlet. The humidity level of the air entering the recovery must be reduced to prevent condensation. There are three ways to reduce the relative humidity of the air; i) increasing the drying air temperature, ii) increasing the drying air flow rate iii) reducing the product flow rate. However, increasing the air flow rate is not a desirable situation as it will increase energy consumption. While the drying air temperature and flow rate are constant, the variable is the product flow rate. This situation is repeated for five different drying air temperatures and five different bypass ratios. The changes in energy efficiency and energy saving are examined. Drying air temperature, drying air flow rate and product flow rate are changeable parameters. However, in order to solve this equation with three unknowns, two unknowns are accepted as a constant coefficient that varies linearly with temperature and the effect of the third one on the others is examined with its change. Here, the constant is accepted as $M_{da}/T_{da}$. For this reason, it is seen that such a ratio is accepted in the literature study [4,5]. The ratio of the drying air temperature and flow rate is taken as constant, and the product mass flow rate is taken as variable. This situation is repeated for five different drying air temperatures and five different bypass ratios. The change in both energy efficiency and savings is examined.

The change in the ratio of the drying air mass flow rate to the product mass flow rate according to five different drying air temperatures and bypass ratios is given in **Figure 2**. When the bypass ratio is reduced (recovery is increased) some parameters need to be changed to prevent condensation in the exchanger. In this study, there are three parameters: drying air temperature, drying air mass flow rate and product mass flow rate. Since the solution of an equation with three variables is complex, the first two parameters are taken as constant, and the product mass flow rate is considered variable. This situation is repeated at five different drying air temperatures and bypass ratios. As the bypass ratio decreases, the mass flow rate of the product decreases, so the $M_{da}/M_p$ ratio increases (from right to left). The air flow rate required to dry one unit of product increases. A high drying air flow rate is undesirable situation because it will increase heating costs.

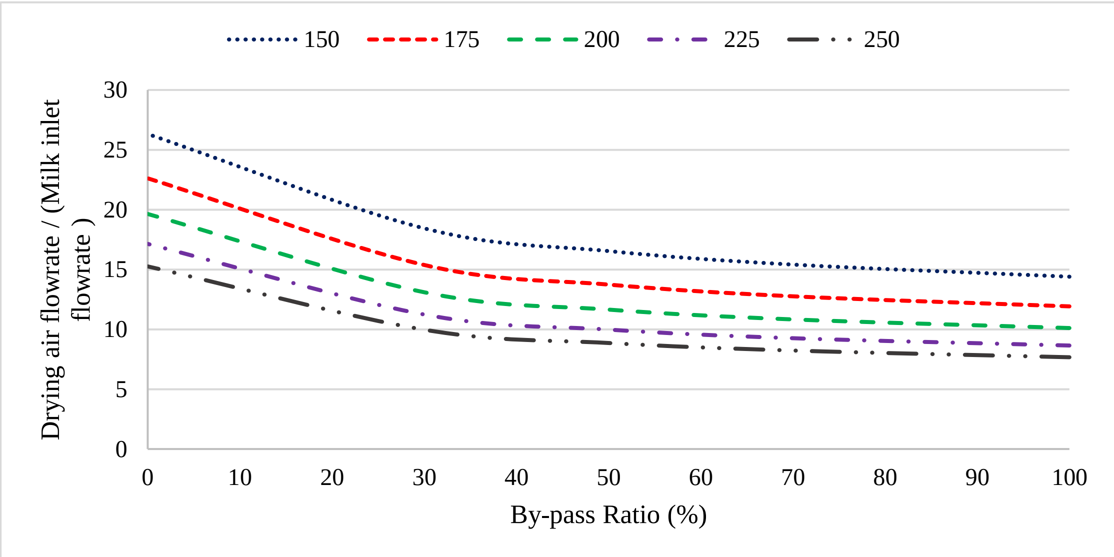



**Figure 2.** Changing of the $M_{da}/M_p$ according to the bypass ratio and drying air temperature (Bypass oranına ve kurutma havası sıcaklığına göre $M_{da}/M_p$'nin değişimi)

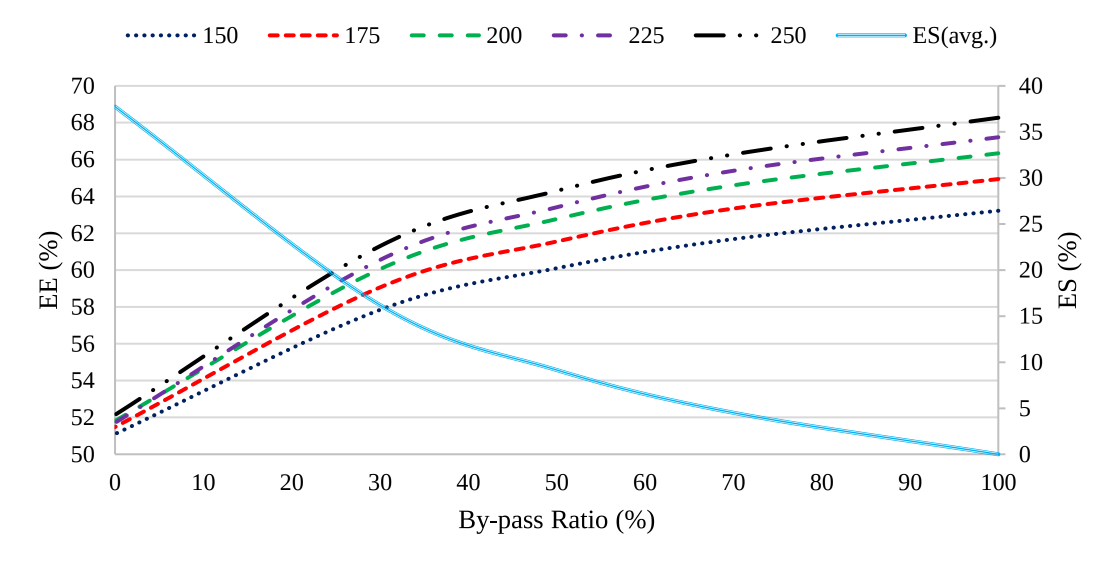


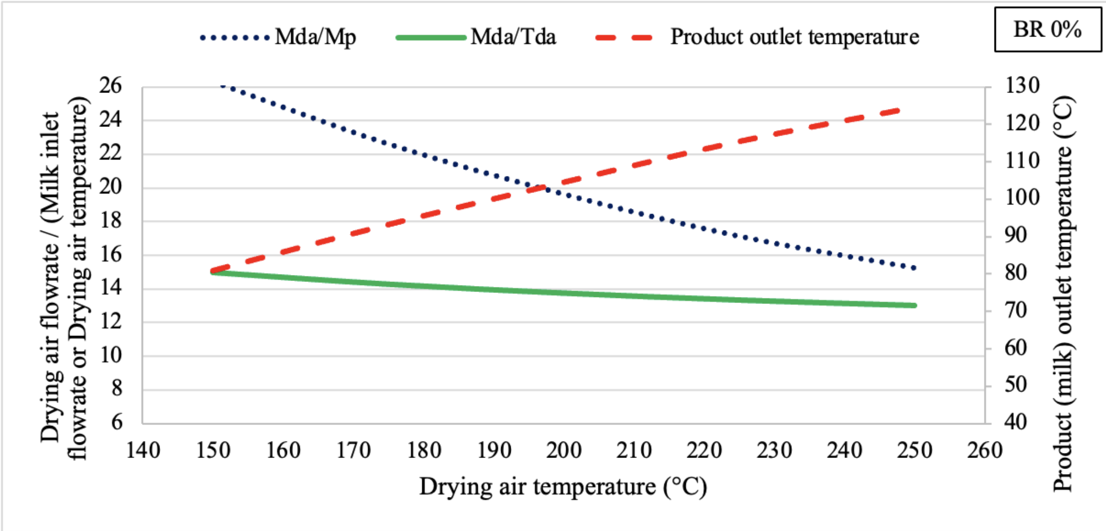

**Figure 3.** Changing of the energy efficiency and energy saving according to the bypass ratio and drying air temperature (Bypass oranına ve kurutma havası sıcaklığına göre enerji verimliliğinin ve enerji tasarrufunun değişimi)

The changes in energy efficiency and energy saving according to bypass ratio and temperature are given in **Figure 3**. It is seen that energy efficiency is higher at higher temperatures. However, the drying air temperature should be decided by paying attention to the maximum temperature that the product to be dried can withstand. Average energy saving values are taken for five different temperatures. After the bypass ratio of 30%, EE gradually increases, and ES decreases significantly. For this reason, the most suitable bypass ratio is 30%, EE values are 57.84 59.06 60.05 60.55 61.3%, ES values are 17.08 16.74 16.23 15.79 15.18% for 150, 175, 200, 225 and 250 ºC, respectively. As bypass ratio increases, energy saving decreases due to the reduced drying air flow rate entering the heat recovery system, while energy efficiency increases. The increase in EE value progresses rapidly up to BR30 and then slows down. **Fig. 3** and **Fig. 2** should be evaluated together. The analyses indicate that the maximum energy efficiency for this system design is approximately 68%, while at the optimal bypass ratio of 30%, the efficiency stabilizes around 60%. A review of the literature confirms that these values are consistent with previous findings [1,5,8]. As the bypass ratio increases, the amount of drying air required for a unit of product decreases, but after BR30 there is no significant change in the $M_{da}/M_p$ ratio (**Fig. 2**).

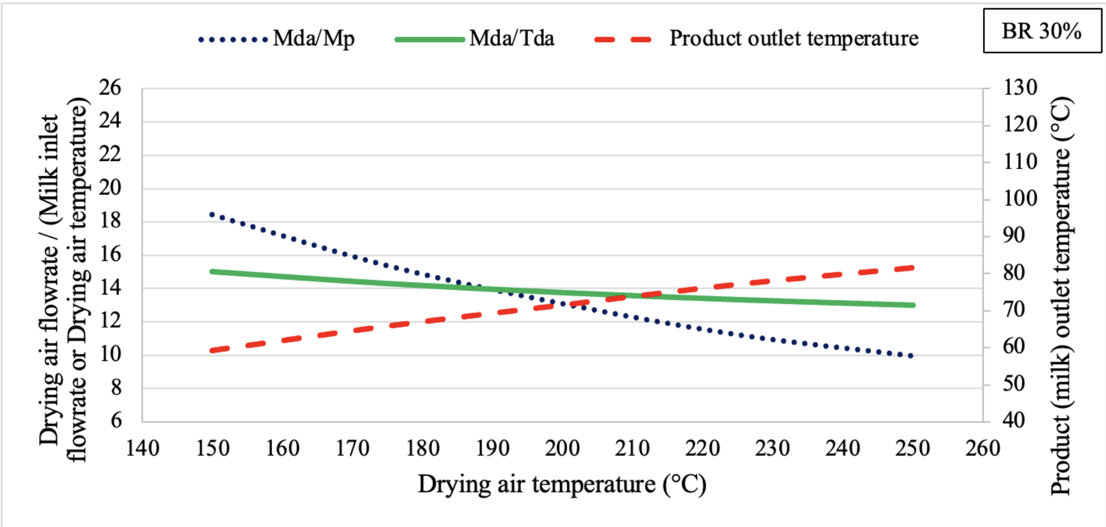
The case where there is no bypass is given as BR0, and the case where all the exhaust air is discharged through bypass without passing through the heat exchanger is given as BR100. Five different bypass ratios (BR) of 0, 30, 50, 70 and 100% are examined. The changes in $M_{da}/M_p$, $M_{da}/T_{da}$, and product outlet temperature are examined according to different drying air temperatures and different bypass ratios such as 0% (**Fig. 4a**), 30% (**Fig. 4b**), 50% (**Fig. 4c**), 70% (**Fig. 4d**) and 100% (**Fig. 4e**).

As the bypass ratio is reduced, that is, as recovery increases, a decrease in the EE value is observed. Because although the amount of energy given to the air is the same, the amount of evacuated water will also decrease since the amount of product entering the dryer is reduced. To find the most effective bypass ratio, it is not enough to look at **Fig. 4** alone; it must be evaluated together with **Figs. 2** and **3**. When looking at the $M_{da}/M_p$ graph according to bypass ratios, a breaking point has occurred in the curve for five different temperatures, this value is 30% bypass ratio. As the bypass ratio decreases, it is seen that the amount of air per unit product increases. Also, when looking at **Fig. 3**, ES is at its highest value at BR 0%, but EE is at its lowest value. As the bypass ratio increases, ES decreases and EE increases. In this case, the most optimum result is seen at 30% BR.

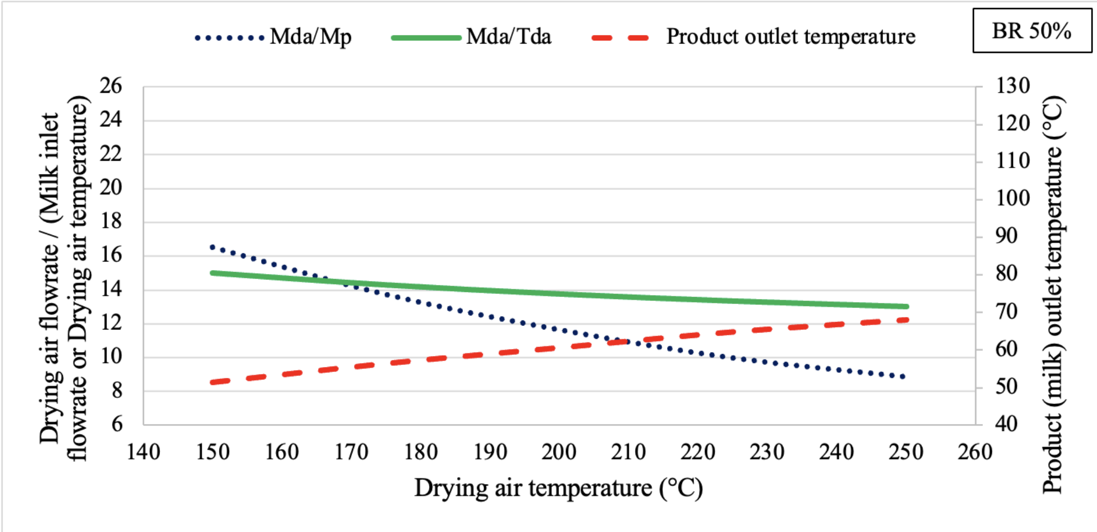
When the bypass ratio is zero, the amount of air required per unit product increases as the product flow rate is reduced to prevent condensation. Drying air at high temperature and flow rate also increases the temperature of the product. High product temperature is not a desired situation for food materials. In addition, a significant decrease is observed in EE. The $M_{da}/T_{da}$ ratio varies between 13-15 in the literature and the average is taken as 14. For this reason, it is seen as a green line with a very low slope in the figures. When BR100, it is seen that the product surface temperature is very low and the $M_{da}/M_p$ ratio decreases, but the energy saving is zero. It is desirable to reduce the amount of air required for a unit of product. The most optimum conditions are seen at BR30%. A review of the literature reveals that Golman and Julklang (2014) [5] and Patel and Bade (2020) [8] align with the findings of this study. The statement of 80% recirculated air in Golman and Julklang's (2014) study [5] is explained with a 20% bypass rate in this study. Similarly, Patel and Bade (2020) [8] which references [5] concludes that a BR ratio of 20% to 30% represents the most optimal conditions.



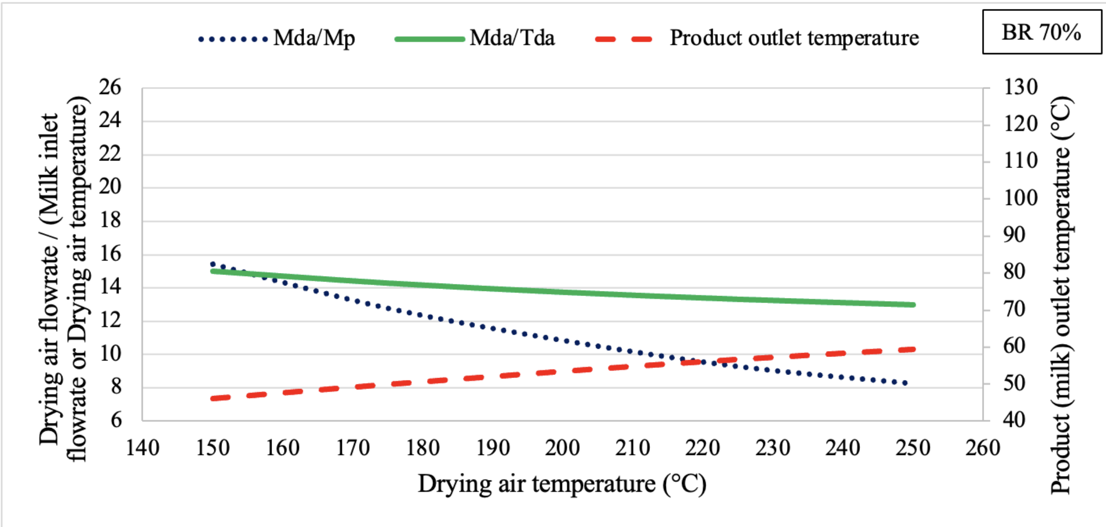

a



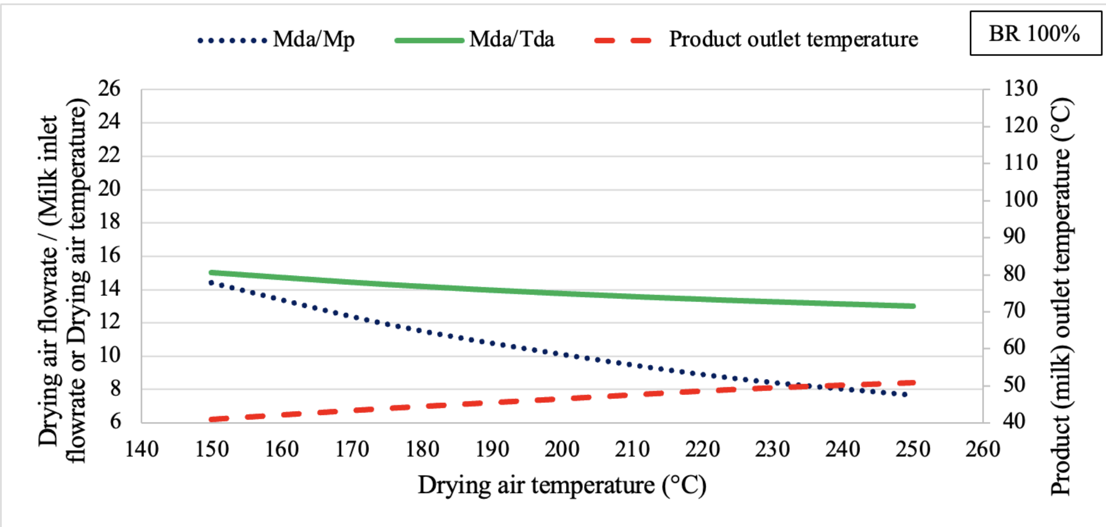

b


Mda/Mp
Mda/Tda
Product outlet temperature
BR 50%
Drying air flowrate / (Milk inlet flowrate or Drying air temperature)
Drying air temperature (°C)
Product (milk) outlet temperature (°C)

c


Mda/Mp
Mda/Tda
Product outlet temperature
BR 70%
Drying air flowrate / (Milk inlet flowrate or Drying air temperature)
Drying air temperature (°C)
Product (milk) outlet temperature (°C)

d


Mda/Mp
Mda/Tda
Product outlet temperature
BR 100%
Drying air flowrate / (Milk inlet flowrate or Drying air temperature)
Drying air temperature (°C)
Product (milk) outlet temperature (°C)

e

**Figure 4.** Comparison of the $M_{da}/M_p$, $M_{da}/T_{da}$ and product outlet temperature according to the drying air temperature and bypass ratio (Kurutma havası sıcaklığı ve bypass oranına göre $M_{da}/M_p$, $M_{da}/T_{da}$ ve ürün çıkış sıcaklığının karşılaştırılması)

## 4. CONCLUSIONS (SONUÇLAR)

In this study, a spray dryer is designed for milk powder production. A heat exchanger is placed at the exhaust outlet to benefit from the exhaust air temperature. If high humidity air meets cold air in the heat exchanger, the RH value of the air will increase, condensation may occur. While exhaust air is discharged, some of the air is bypassed and mixed at the exchanger outlet to prevent condensation. The effects of different bypass ratios on energy efficiency and energy saving are investigated.

There are three main parameters affecting the dryer performance: drying air flow rate, drying air temperature, and product flow rate. Initially, the ratio of first two parameters is kept constant, and the performance is examined by varying a single parameter at time. A heat exchanger is placed at the dryer outlet to recover heat from the exhaust air. However, since the relative humidity of the exhaust air is at 50-60%, there is a risk of condensation in the exchanger when it meets the fresh air. In order to prevent condensation in the exhaust air, some of the air is bypassed and given to the mixing chamber at the exchanger outlet. When the bypass ratio is 100% (when recovery is not used), EE reaches its highest value, because more product is dried, but ES is zero. In order to prevent condensation in the heat exchanger, the drying air flow rate or drying air temperature can be increased. However, these are assumed as constant coefficient. Another alternative is to reduce the product flow rate, in this way the drying air will be at a lower RH level because less water will be evaporated. This process is repeated for five different drying air temperatures and bypass ratios. When the results are examined, it is seen that the best bypass ratio is 30%. At drying air temperatures between 150-250°C and a BR30%, EE varies between 57.8% and 61.3%, while ES ranges from 15.18% to 17.08%. As the BR decreases, a drop in EE is observed due to the reduced product mass, which prevents condensation. Additionally, at lower BRs, the product outlet temperature rises significantly. To maintain product quality, it was found that the maximum acceptable product outlet temperature of 60°C could be achieved at BRs of 30% or higher. However, the best energy efficiency and energy saving values are obtained at bypass ratios of 40% and below. It is thought that the results obtained in this study will guide future studies.

As a result of this study, it is found that the greatest challenge for spray dryers with high air consumption is the condensation of the exhaust air, which exits the drying chamber at high temperatures and relative humidity, within a HR system. Two popular methods to prevent condensation in the HR unit are dehumidification via cold surfaces and the use of additional materials like silica gel. While condensation could be prevented through dehumidification on cold surfaces, the heat transfer performance significantly reduced. Moreover, the application of silica gel are extremely costly solutions for these systems with high air consumption and would require constant replacement, making them impractical.

## DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the methodology she uses in her work does not require ethical committee approval and/or legal specific permission.

Bu makalenin yazarı çalışmasında kullandığı materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan eder.

## AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Gülşah KARACA DOLGUN*:** She conducted the calculations, analyzed the results and performed the writing process.

Hesaplamaları yapmış, sonuçları analiz etmiş ve yazım sürecini gerçekleştirmiştir.

## CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

## NOMENCLATURE (TERMİNOLOJİ)

| | |
|---|---|
| $c_p$ | specific heat capacity (kJ/kg K) |
| h | enthalpy (kJ/kg) |
| $h_e$ | evaporation enthalpy (kJ/kg) |
| m | mass (kg) |
| T | temperature (°C) |
| Q | heat transfer amount (kJ) |
| X | the mass fraction of water on dry basis (kg $kg^{-1}$) |
| Y | the humidity on dry basis (kg $kg^{-1}$) |

| | |
|---|---|
| $\lambda_{ref}$ | the latent heat of vaporization of water at $T_{ref}$ (kJ/kg) |
| $\eta_R$ | energy efficiency (%) |
| *Subscripts* | |
| a | fresh air inlet |
| ai | drying air inlet |
| ao | drying air outlet |
| hi | recovery air |
| in | inlet |
| i | in state i |
| mi | milk inlet |
| mo | milk powder outlet |
| out | outlet |
| rec | recovery |
| ref | reference |
| req | required |
| v | vent air |

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