Heat Recovery Characteristics and Energy Efficiency Analysis of a Heat Pump-Fine Filament Water-Film Sucrose Drying System

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Abstract

Given the problems of high energy consumption, poor utilisation of exhaust heat, and low sugar dust recovery efficiency in traditional sucrose hot-air drying, this paper presents a heat pump-coupled fine-filament water-film sucrose drying system and studies its heat recovery characteristics and energy performance. The condenser side of the heat pump in the proposed system supplies drying heat, and the evaporator side provides low-temperature circulating water to maintain a stable liquid film on the fine filaments for integrated drying, exhaust heat recovery and wet sugar dust capture in a unified process. According to the system's structure, this paper outlines the primary heat-transfer paths, the functional purpose of the recovery unit, and an energy-efficiency assessment system; at the same time, it investigates how to modify operating parameters to increase heating capacity and heat-recovery intensity for the entire system. Based on the above analysis, connecting a heat pump with a fine-filament water-film unit can reduce sensible and latent heat loss in the exhaust stream, improve the utilisation of recirculated air, and enhance cascade use of thermal energy in the system. At the same time, a liquid-film interface can increase the efficiency of particle collection and provide a good environment for the re-absorption and redistribution of exhaust heat. Introduce indicators such as the coefficient of performance, specific moisture extraction rate and heat recovery ratio to assess the energy-saving effect and engineering feasibility of the system in an all-around way. Provide the foundation for the following experiments and numerical simulations of low-carbon sucrose drying equipment: experimental verification and engineering optimisation.

Keywords

Heat Pump; Fine-Filament Water Film; Sucrose Drying; Heat Recovery; Energy Efficiency; Sugar Dust Recovery.

1. Introduction

Sucrose drying is the last treatment in the sugar industry that directly affects the water content of the final product, flow characteristics and storage stability, etc. Traditional sucrose drying generally uses a hot-air convection system; although technologically mature, these systems often have a low thermal utilisation efficiency and substantial exhaust heat loss, thus being relatively high in specific energy consumption. With the increasing demands for industrial decarbonisation, it is now necessary to improve the energy efficiency of sucrose drying equipment and maintain product quality. At the same time, the problem of management for sugar dust has also arisen. During drying, conveying, sieving and packaging, fine sugar particles are often carried in the exhaust air; this results in material loss, equipment fouling, environmental pollution and a risk of dust explosion. Recently, studies on sugar dust management have begun to treat sugar dust as a problem of process safety and resource recovery in relation to plant operations, in addition to an environmental problem [1]. Therefore, optimisation

Volume 12 Issue 8, 2026
DOI: 10.6919/ICJE.202608_12(8).0005

of sucrose drying systems should move away from a narrow focus on heat supply and address issues such as drying efficiency, heat recovery, particulate capture and operational safety in an all-encompassing way.

Heat pump technology has attracted the attention of many people in the drying and industrial low-temperature heating fields because it can recover low-grade thermal energy and increase its temperature. Previous research has shown that heat pump drying systems can improve the energy efficiency of temperature-sensitive processes to some extent compared with traditional electric or fossil-fuel heating methods [2-5]. Research on cold-surface particle deposition, thermophoretic transport and wet dust collection have shown that low-temperature interfaces and structured gas-liquid contact zones can promote the migration and collection of fine particles [6-8]. Based on the above results, a fine-filament water-film interface can be used to remove particles and enhance both heat and mass transfer at the interface for cooling. Although existing studies have conducted separate research on heat pump drying, wet particle capture and industrial heat recovery, there is a scarcity of research on an integrated "heat pump-fine filament water film-sucrose drying" system that coordinates heat recovery and energy efficiency assessment. Based on the above, this paper investigates a heat pump-coupled fine-filament water-film sucrose drying system and examines the system's structure, heat recovery method and energy performance.

2. System Configuration and Research Method

2.1 Overall System Configuration

The heat pump-fine filament water-film sucrose drying system introduced in this paper consists of a heat pump cycle, a drying chamber, an exhaust recirculation section, a fine-filament water-film capture unit, and a sugar solution recovery section. The condenser of the heat pump supplies a stable hot air to the drying chamber during operation to remove moisture from the sucrose material, and the exhaust stream is directed to a fine-filament water-film unit where low-temperature liquid films collect sugar dust and absorb some of the residual heat before the treated air is either recirculated or discharged. As shown in Figure 1, the first characteristic of this type of arrangement is that both the hot-side and the cold-side components of a heat pump have been included in the process utilization chain. A condenser is employed at the end of drying to dissipate heat and form a stable, low-temperature liquid film on the fine filaments at the evaporator end. Compared with a traditional series connection of a hot-air dryer and an independent dust collector, the current system has increased the extent of closed-loop energy use and functional coupling among unit operations.

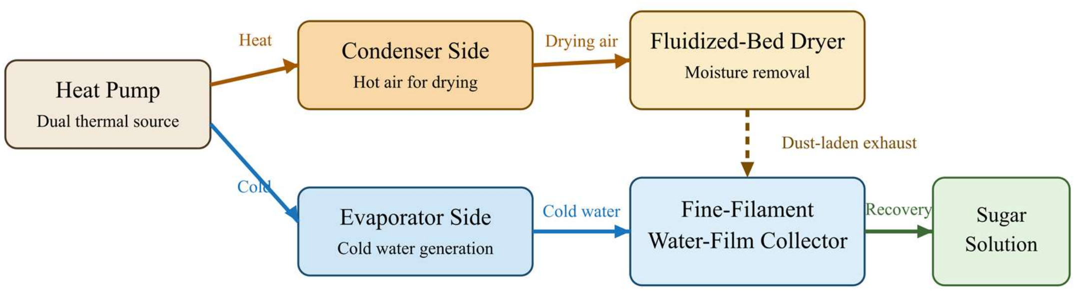

Figure 1. Schematic configuration of the heat pump-fine filament water-film sucrose drying system

2.2 Heat Recovery Pathways

The three connections of heat recovery in the new system are shown below. First, some of the sensible heat in the drying exhaust is recovered by air recirculation and thermal exchange to reduce the requirement for fresh-air reheating. Second, a part of the latent heat of water vapour in the exhaust gas can be recovered at the evaporator end of the heat pump and then released at the condenser end for drying. Third, a fine-filament water-film unit is used to absorb some of the residual heat in the

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0005

exhaust gas and collect sugar dust; thus, a smaller amount of usable heat is lost to the surroundings. From a thermodynamic standpoint, a heat pump can be used to recover low-grade heat dispersed in the exhaust and raise its temperature to a suitable level for use in the drying stage; thus, the fine-filament water-film section serves as an intermediary link between exhaust treatment and thermal redistribution and can be employed for both heat recovery and material recovery.

3. Mechanisms and Energy Efficiency Evaluation

3.1 Enhancement Mechanisms of the Fine-Filament Water Film

The purpose of the fine-filament water-film unit is also not to collect physical particles. Moreover, it is a combined heat- and mass-transfer junction that can also achieve gas-liquid contact and locally generate a temperature gradient and recover soluble particles simultaneously. When the dust-laden exhaust passes through the filament array, sugar particles may be carried to the low-temperature liquid film by inertial impaction, interception and adhesion, Brownian diffusion, and thermophoretic migration. Sugar dust is highly water-soluble; therefore, the particles at the interface can dissolve in the liquid film and be converted into a reusable sugar-solution stream. As shown in Figure 2, the cold liquid-film interface is thus a multi-mechanism capture boundary. Larger particles are more likely to impact the film due to inertia; intermediate-sized particles are prone to being intercepted and adhering to the filament surface, and fine particles may be affected by temperature gradients and local flow disturbances that promote enrichment near the low-temperature film. That is to say, the fine-filament water-film unit can also help to create a good environment for heat recovery and solution reuse by removing particles.

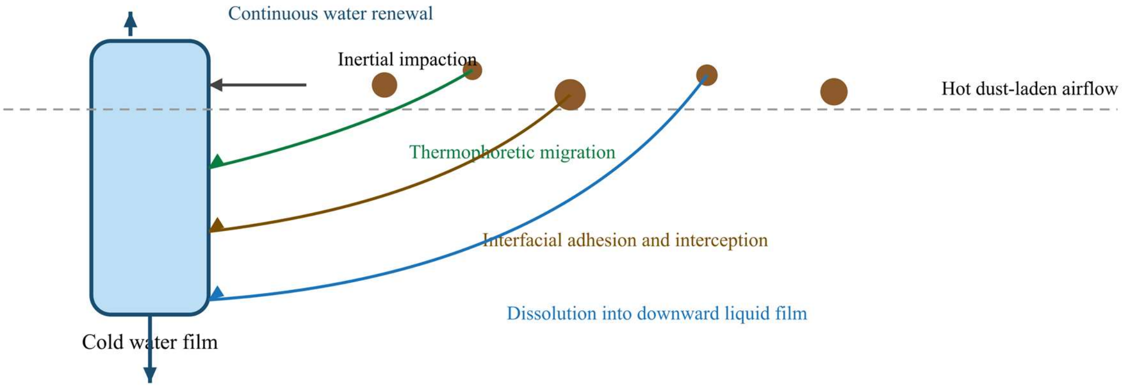

Figure 2. Main mechanisms of sugar dust capture at the cold fine-filament water-film interface

3.2 Energy Efficiency Indicators

A number of combined indicators are used to evaluate the thermal and energetic performance of the proposed system, rather than a list of several individual measures. The coefficient of performance is defined as the ratio of condenser-side heating output to total electrical power input, and it can be regarded as a direct indicator of the energy-upgrading capacity of a heat pump or a whole-system thermal efficiency measure. The particular moisture extraction rate is the amount of water removed per unit of energy supplied, and thus can be employed to compare the drying performance at different operating conditions. The ratio of heat recovery can be used to find out how much of the recoverable exhaust heat will be used in the process. At present, in the case of sucrose drying, these traditional thermal indicators should be supplemented with process-oriented parameters, such as sugar dust removal efficiency, recovered sugar solution yield, and total energy consumption per unit of product

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0005

output. Collectively, the above indicators can be used to evaluate whether the system is only a heat pump dryer or an all-in-one thermal recovery and material recovery platform.

4. Results and Analysis

4.1 Analysis of Heat Recovery Characteristics

According to the system arrangement and thermal flow structure, a heat pump can be employed in conjunction with a fine-filament water-film unit to convert exhaust air from a source of energy loss into an active internal heat-redistribution device. As shown in Figure 1, the drying section, recirculation path and capture section together form a relatively closed thermal loop. The new system can recover some of the sensible and latent heat from the exhaust in the open-air-drying method by means of recirculation and heat pump upgrading to improve the overall thermal use efficiency. In theory, the heat recovery ratio should increase with an increase in the recirculation fraction and when the thermal condition of the exhaust is closer to that of the evaporator side. Air recirculation is too high; therefore, the driving force for drying will be reduced, affecting both the final moisture content and drying speed of sucrose. Therefore, the goal should not be to maximise heat recovery at all costs; rather, a good combination of energy-saving and drying-quality objectives needs to be realised.

4.2 Influence of the Fine-Filament Water-Film Unit on System Energy Performance

The new fine-filament water-film unit is no longer only a dust-removal device at the end of the line; it has now been upgraded to an active thermodynamic element for the whole process. At the same time, a unit reduces the concentration of sugar dust in the exhaust gas and increases material recovery. At the same time, a low-temperature liquid film with a large specific contact area can be used to increase heat absorption from the exhaust gas and provide a more stable thermal boundary condition for the evaporator side of the heat pump. As a result, the system may have a higher coefficient of performance and a lower specific moisture-extraction-energy demand under the same drying load. Figure 2 shows that the cold liquid-film interface creates an ideal gas-liquid-exchange region where both particle capture and thermal interaction can occur simultaneously; thus, this interpretation is supported. Optimise the spacing of the filament, liquid-film flow rate and circulating water temperature to further increase the efficiency of dust collection and enhance heat absorption at the evaporator end; thus, the overall energy performance of the system will also be improved.

4.3 Validation Framework

The following experiments are to be supported by a validation framework based on the system design, mechanism analysis, experimental verification and energy-efficiency assessment, as shown in Figure 3. The first purpose of this system is to prevent the following work from being confined to the stage of describing conceptual equipment, but to gather quantitative data on the impact of various operating factors. Figure 3 shows that the future experiments may be based on factors such as hot-air temperature, circulating water temperature, recirculation ratio, filament diameter, liquid-film flow rate and dust concentration. Combine system-level heat and mass balances with experimental drying and capture performance to quantify the heat recovery ratio, coefficient of performance, specific moisture extraction rate and recovered sugar solution yield under various operating conditions in future research.

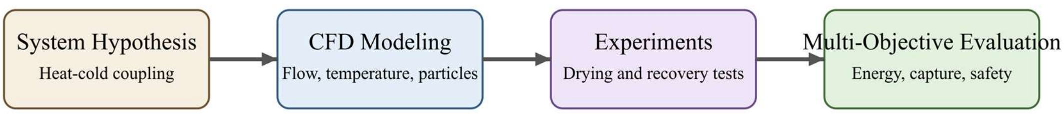

Figure 3. Validation framework for the heat pump-fine filament water-film sucrose drying system

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0005

5. Conclusion

This paper investigates the heat recovery and energy performance of a heat pump-fine filament water-film sucrose drying system. According to the analysis, the condenser side of the heat pump can supply the heat demand for drying; at the same time, the evaporator side and the fine-filament water-film unit work together to expand exhaust heat recovery and sugar dust collection, forming an integrated heat recovery and material recovery platform. Figure 1 shows the system structure and thermal circulation path; Figure 2 presents the multi-mechanism capture behaviour of sugar dust at the cold liquid-film interface; and Figure 3 is a validation framework for the following experiments and numerical calculations. Generally speaking, the topic of heat recovery characteristics and energy-efficiency analysis for a heat pump-fine filament water-film sucrose drying system is worth studying.

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