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Performance comparison of an adiabatic and an internally cooled structured packed-bed dehumidifier

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ABSTRACT

Liquid desiccant dehumidifiers are used to improve the indoor air quality and achieve lower humidity levels in conditioned spaces. The performance of these dehumidifiers can be enhanced by providing simultaneous cooling in them. This paper presents the performance comparison of an adiabatic and an internally cooled structured packed-bed dehumidifier. The non-adiabatic structured packed-bed absorber consists of rigid media pads with cooling water flowing through the tubes embedded in the packing. The desiccant ($CaCl_2$ in this study) falls by gravity while air flows in the cross flow configuration. The performance of this absorber has been evaluated at varying desiccant flow rates. The moisture removal from the air, the effectiveness of the dehumidifier and the mass transfer coefficients between air and solution have been compared for the dehumidifier operation with and without internal cooling. It is found that the optimum liquid to gas flow rate ratio for maximum effectiveness is about 1.0.

1. Introduction

Desiccant dehumidifiers are emerging as a promising alternative to achieve humidity control in variety of applications with high latent loads and low humidity requirements such as in supermarkets, pharmaceuticals, etc. Both solid and liquid desiccants are being used in practice, but liquid desiccant absorbers are becoming more attractive because of the possibility of simultaneous cooling during the process of dehumidification. Liquid desiccants also have the capability to absorb inorganic and organic air contaminants and microorganisms (Chung et al. [1]; Oberg and Goswami [2]). Aqueous solutions of inorganic salts such as lithium chloride, lithium bromide, and calcium chloride etc. are commonly used as liquid desiccants to minimize the problem of carryover as the salts exert negligible vapor pressure. Zero carryover designs have been reported by Lowenstein [3], Asati [4] and Kumar [5]. The problem of corrosion commonly encountered while using salt solutions is eliminated by using suitable materials of construction, typically polymeric substances such as polypropylene, acrylic, PVC etc. Crystallization problem can be avoided by maintaining the concentration of solution at a level lower than the solubility limit corresponding to the operating temperature. The desiccant can be regenerated using solar energy or waste heat in order to conserve the primary energy sources.

Comprehensive literature reviews on different types of liquid desiccant systems have been presented by Öberg and Goswami [2] and Jain and Bansal [6]. The latter review provides an overview of various liquid desiccant systems and summarizes their experimental performance. Spray towers, falling film towers and packed bed towers are the commonly used designs of desiccant dehumidifiers. It is clear from the literature that structured packed bed towers are quite popular due to their high effectiveness and low pressure drop (Esam et al. [7]). Although internal cooling is common in spray towers and falling film towers, packed bed towers are generally adiabatic absorbers and there is no study in the open literature on structured packed-bed absorbers with internal cooling. The heat evolved during the process of dehumidification increases the temperature of both the solution and the air. Thus the equilibrium vapor pressure of solution increases and the potential for moisture absorption decreases. To remove the released heat and to maintain high mass transfer potential throughout the absorber, a cooling medium is circulated within the absorber, which is termed as internal cooling. It has been reported by Jain and Bansal [6] that internal cooling can increase the humidity effectiveness of an absorber to values even greater than one. In such cases, the outlet humidity of air falls below the inlet equilibrium humidity of solution. This happens due to fast cooling of solution below its inlet temperature, as it flows through the absorber especially when the

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inlet solution temperatures are high. This phenomenon is possible only for internally cooled absorbers with high solution inlet temperature. Internal cooling also eliminates the need for a separate solution precooler before the absorber.

Chung and Wu [8], Deng and Ma [9], Islam et al. [10,11], Jain et al. [12], Mesquita et al. [13] and Scalabrin and Scaltri [14] provided simultaneous cooling in an absorber by circulating cooling water. Sprayed coils, cross flow plate heat exchangers, and falling film absorbers are some of the designs that have been used to provide simultaneous cooling by water. Khan [15] presented heat and mass transfer analysis of an internally cooled liquid desiccant absorber, which was considered as a spray finned tube heat exchanger. A two-dimensional steady state model was developed and solved numerically. Based on the NTU-effectiveness methodology, a performance prediction model was developed to estimate the annual energy requirements of the system using an hour-by-hour analysis. Mesquita et al. [13] developed mathematical and numerical models for internally cooled falling film dehumidifiers, using heat and mass transfer correlations. Yin et al. [20] proposed using a plate fin heat exchanger design as an internally cooled dehumidifier and as an internally heated regenerator. Internally cooled dehumidifier was shown to have higher dehumidification performance compared to an adiabatic dehumidifier. Yin and Zhang [21] reported higher regeneration rate and regeneration thermal efficiency (defined as heat required to vaporize the moisture to the heat supplied) compared to an adiabatic regenerator. Liu et al. [22] simulated the performance of internally cooled dehumidifiers with different flow configurations of air and desiccant. Counter-flow configuration was reported to have the best dehumidification performance. The performance of a cross-flow internally cooled dehumidifier was also compared with that of an adiabatic dehumidifier plus an external heat exchanger. Internally cooled dehumidifiers were found to have better mass transfer performance under similar operating conditions.

This paper presents the performance data of a structured packed bed tower with the provision for internal cooling and compares its performance with a similar absorber without internal cooling. The structured packed tower consists of rigid media pads made of cellulose paper and is used in cross-flow configuration for ease of construction and maintenance as it reduces the height of the tower and integrates it easily into the duct system, although it will tend to have lower heat and mass transfer effectiveness. Cooling tubes are impregnated into the cellulose packing. Calcium chloride is used as a desiccant as it is cheap, although it is not as effective as other salt solutions, due to its higher vapour pressure (Chung and Luo [16]).

2. Experimental setup

An advanced experimental rig was developed in the Thermodynamics Laboratory (at The University of Auckland) to understand the simultaneous heat and mass transfer process while the liquid desiccant removes moisture from the humid air stream. The rig (see Fig. 1) has a structured packing dehumidification system using $CaCl_2$ as a liquid desiccant and a cooling system within the dehumidification pad tower. The rig comprises of three parts. Part 1 consists of air supply and controls the relative humidity, temperature and velocity conditions of the inlet air. Part 2 consists of desiccant distribution system and controls the concentration, temperature and flow rate of the desiccant. Part 3 consists of the cooling system, which supplies coolant at a certain temperature and flow rate through the dehumidification pad packing tower to provide cooling during the heat and mass transfer process. The ducting is made out of 8 mm thick clear acrylic (to allow visual observation).

As may be seen from Fig. 1, a centrifugal fan, fitted at the end of the duct, draws ambient air through the duct. The flow rate of the air is controlled by adjusting the speed of the fan. To achieve the desired humidity of air at the inlet of the packed tower, an atomizing nozzle and a heating system was added to heat the water to 85 °C. Although steam injection would have been a better option, it was not permissible due to safety reasons and hence hot water spray with air heaters was used as an alternative option. The air flows over a series of heaters that heat the air to the required temperature. The heater power input is controlled by a variable transformer (Variac). Air mixer was used to get homogenized mass of air for measurement of its average properties, while tap water was used in the eliminator to remove any carryover of the salt (along with air) and any deposits of salts on the eliminator pads.

The heated and humidified air flows through a drift eliminator pad, which eliminates water droplets and lets the air to pass through it. The pads are made of cellulose and are structured similar to a honeycomb. The water droplets retained in the drift eliminator pad are drained at the bottom. The inlet conditions to the packed tower are monitored by wet-and dry-bulb thermocouples located after the eliminator. The hot and humid air is then drawn through the packed bed tower which consists of cellulose paper pads with a flute angle of 45° and a packing density of 608 m^2/m^3. The aqueous solution of $CaCl_2$ working as liquid desiccant is sprayed at the top of the absorber onto the sponges, which sit on top of the Celdek pads. The desiccant to air flow arrangement is a cross-flow configuration with a face area of 0.09 m^2 and height of 0.3 m. The cooling water sub-system consists of a chiller, heaters, cooling coil, connecting hoses and rotameter. The cooling coil is made of 7.13 mm ID aluminum tubes arranged in 6 rows and 4 passes. The inlet and outlet temperatures are measured and logged using thermocouples. The humidity and temperature of the dehumidified air is also recorded at the outlet of the dehumidifier. The air flows through another drift eliminator to remove any $CaCl_2$ droplets before it is blown out of the duct by the fan.

The liquid desiccant is sprayed on the pads by pressurizing the desiccant tank with compressed air as shown in Fig. 2. A steel drum with an epoxy inner coating is used as desiccant tank to protect it from corrosion and to sustain the pressure. The pressure in the desiccant supply tank controls the mass flow rate of the desiccant through the rig. A stirrer is fitted inside the drum to prevent stratification as the solution is heated. To accurately control the desiccant temperature and flow rate at the inlet of the pads, a control valve and an inline heater are fitted in the line after the supply tank. The inline heater is also controlled by a variable transformer. A thermocouple and a flow meter connected to the data logger monitor the desiccant inlet conditions as required. All the measurements were recorded in a data logger at 30 s intervals. Due to the restricted space and budget, the current facility was designed to carry out experiments in one mode only viz. regeneration or dehumidification at a time. Once the strong solution tank gets emptied, the regeneration of solution is carried out by opening and closing the appropriate valves and heating the solution as shown in Fig. 1. It may also be noted that the tests aim to reproduce the real conditions of a conventional process where, when dehumidifying the air, the concentration of the solution is maintained at high temperature coming from a regeneration process. The control of the heating process aims to control the feed temperature, but it should be noted that in the current setup, the solution is heated to the desired temperature through two solution heaters, the second one being an inline heater operated by a temperature controller.

3. Measurements and instrumentation

The concentration of the calcium chloride solution is calculated by measuring its temperature and specific gravity relative to the