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Experimental and numerical studies on the treatment of wet astronaut trash by forced-convection drying

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ABSTRACT

During long-term space missions, astronauts generate wet trash, including food containers with uneaten portions, moist hygiene wipes and wet paper towels. This waste produces two problems: the loss of water and the generation of odors and health hazards by microbial growth. These problems are solved by a closed-loop, forced-convection, heat-pump drying system which stops microbial activity by both pasteurization and desiccation, and recovers water in a gravity-independent porous media condensing heat exchanger. A transient, pseudo-homogeneous continuum model for the drying of wet ersatz trash was formulated for this system. The model is based on the conservation equations for energy and moisture applied to the air and solid phases and includes the unique trash characteristic of having both dry and wet solids. Experimentally determined heat and mass transfer coefficients, together with the moisture sorption equilibrium relationship for the wet material are used in the model. The resulting system of differential equations is solved by the finite-volume method as implemented by the commercial software COMSOL. Model simulations agreed well with experimental data under certain conditions. The validated model will be used in the optimization of the entire closed-loop system consisting of fan, air heater, dryer vessel, heat-pump condenser, and heat-recovery modules.

1. Introduction

Like people on earth, astronauts living in space also produce garbage. This "space trash" is mostly used food and drink containers which may have unconsumed portions, dirty hygiene wipes and paper towels, plastic packaging, and paper [1]. The current treatment of space trash is storage and then disposal. During the Space Shuttle missions, which generally lasted less than 16 days, trash was compressed in small bags, wrapped with duct tape, and then returned to earth [2]. In the International Space Station (ISS), trash bags are stored and periodically removed by the Russian Progress spaceship or private American space cargo crafts. For manned missions to distant destinations, such as a rendezvous with an asteroid or future Mars landing, resource recovery and stabilization of trash will be critical for success. A four-person crew is estimated to discard 1 kg day $^{-1}$ of water in their trash [3] and recovery of this water will reduce payload mass and associated lift costs. Microorganisms can colonize the wet trash, especially the food and hygiene wipes, and as the experience of Mir and ISS demonstrates, microbial growth may lead to the generation of odors, allergens, and potential health hazards [4, 5].

Drying of the space trash by hot-air forced-convection can stop microbial activity by combined pasteurization and desiccation, with the water vapor produced recovered by a condenser. Our research group, together with Orbital Technologies Corp. (ORBITEC), studied a closed air-loop, dryer and condenser system for astronaut trash. The system consists of a blower, air heater, wet material vessel, a gravity-independent Porous Media Condensing Heat Exchanger (PMCHX), thermoelectric heat pump, and waste heat recovery module (Fig. 1). The process may be adapted for drying crew laundry, recovering water from water-reprocessing brines, and dehydrating food and biomass from future bioregenerative systems.

Drying is extensively used in agricultural post-processing and in the food, pharmaceutical and chemical industries. Its importance is evident in the large number of publications on drying principles, models, and sample-specific data in the literature. Several books have been written on the topic [6–9] and there is a journal dedicated to it (Drying Technology, Taylor & Francis, Philadelphia, PA). The drying of astronaut cabin waste or any type of trash, however, has not been reported. Drying is an energy-intensive process and becomes economical only for a high-value product, which trash is not. In long-term space missions, the water in the wet trash is valuable enough to justify recovery by drying, but energy efficiency is

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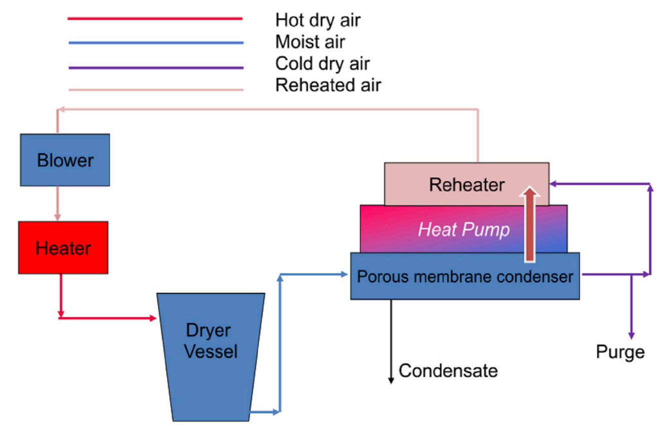

Fig. 1. Schematic for the closed-loop drying system for space trash.

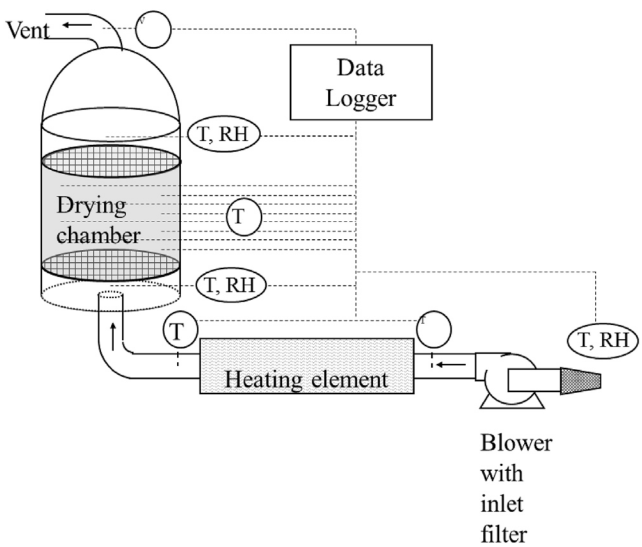

Fig. 2. Experimental set-up used for trash drying.

trash drying component in that model. The experimental studies needed to obtain model parameters and data for validation were conducted in an open air-loop prototype constructed for research on the heat and mass transfer aspects of trash drying (Fig. 2). The prototype was designed in collaboration with and fabricated by ORBITEC.

2. Model development

2.1. Problem description

The cylindrical dryer is represented by an axi-symmetric geometry (Fig. 3). The trash bed is modeled as porous media with large pores [10, 11]. It is assumed that a pseudo-homogeneous continuum model can be used for the system [12]. The control volume contains both solid and gas phases, each having a different temperature (two-temperature model). Wet and dry pieces of trash make up the solid phase while the gas is humid air. The walls of the cylindrical dryer are assumed to be perfectly insulated, making the temperatures and moisture contents of the solid and gas phases a function only of the distance from the bottom (1-D model, variation along the z-axis only).

2.2. Model assumptions

Simplifying assumptions were used in the model. The bed porosity and dry solid composition are assumed to be both space and time invariant (negligible shrinkage and settling). The physical and transport properties of the trash and humid air do not significantly change across the operating temperature range (25–60 °C). Constant air velocity throughout the bed is assumed since: (1) expansion of the gas due to decrease in pressure is negligible (observed pressure drop between inlet and outlet air <10 mmHg), (2) the increase in mass flow from addition of water vapor to the gas stream was always less than 3.5% (10–80% humidity at 30 °C), and (3) the maximum air temperature change, from the entering air temperature of 60 °C to the cold bed temperature of 25 °C, corresponds only to a 10% increase in air volume. Diffusion of water in the solid bed is assumed to be negligible.

The wet and dry pieces in the trash are expected to have different temperatures during drying. Evaporation of water in the wet materials would keep their temperature near the wet-bulb temperature (≈25 °C) while the dry components would approach that of the hot air passing

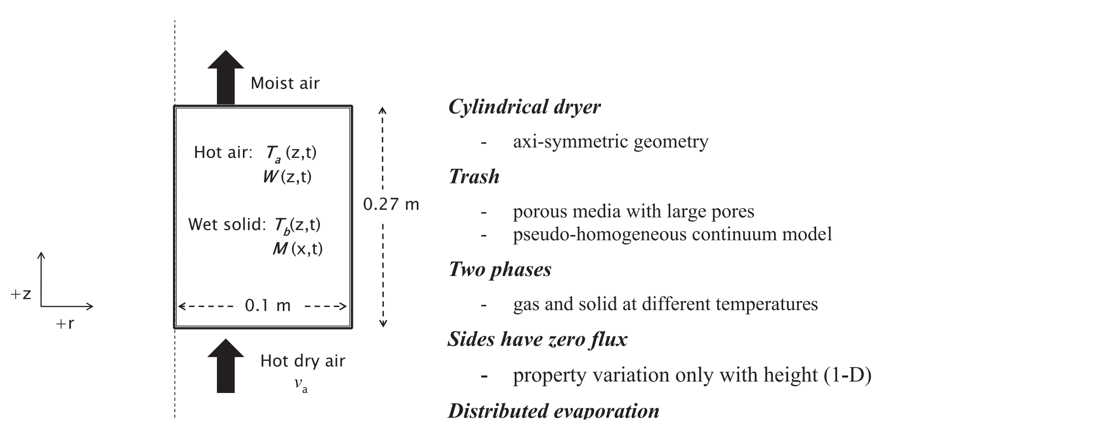

Fig. 3. Schematic of the axi-symmetric computational domain used in the model. The dryer is represented by a pseudo-homogeneous continuum model with two phases: gas and solid. The variables of interest are the temperature and moisture content in each phase.

still needed for maximum benefit. A computational model for the drying of space trash would guide the optimization of a drying system such as the closed-loop, forced convection process investigated by our research group.

This paper presents the formulation and validation of the packed-bed

them. In most cases the dry pieces will be hotter than the wet ones, and though they are in contact with each other, the heat conduction between them is assumed to be negligible. This assumption is likely valid since loose packing of the trash (porosity = 0.91) greatly reduces the area for heat transfer by conduction.