Energy Conversion and Management 50 (2009) 1570–1577

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Delineation of frost characteristics on cold walls by using a new formula for psychrometrics demarcation boundary

Ahmed Hamza H. Ali *

Department of Mechanical Engineering, Faculty of Engineering, Assiut University, Assiut 71516, Egypt

ARTICLE INFO

Article history:
Received 9 July 2008
Accepted 10 February 2009
Available online 19 March 2009

Keywords:
Frost
Cold storage
Psychrometric chart
Evaporator
Coil
Performance

ABSTRACT

In this study, a direct formula that predicts either the frost formation on cold walls is correspondence to psychrometric-subsaturated or supersaturated regions is presented. The developed formula uses the data of the entering air dry-bulb temperature and absolute humidity, and the absolute humidity of the air at saturation corresponding to the coil surface temperature. Cases studies of demarcation criteria for frost formation on evaporator coil using experimental measured data, and on walls of cold storage freezer using measured data from literature are used to validate the formula and it is found that results are completely matches to the graphic plot of the data on the psychrometric chart. In case of cold storage freezers, the result clearly shows that a greater demarcation criteria value indicates frost formation under sever condition that is characterized as snow-like with low density and thermal conductivity.

1. Introduction

Frost problems often occur in cold storage freezers because of the infiltration of warm humid air through access doors. When the cold storage freezer door open, air at the upper layers in the docks rushes inside the freezer to replace the exfiltrated air and mixes with the freezer air in the upper layers of the freezer. This air mixture creates, inside the freezer, fog and ice fog crystals that deposit on the freezer walls and products. Also, as moist air is cooled by passing over evaporator coil that has surface temperature below both the dew point and the freezing point of the air in the vicinity of the coil surface, frost forms and deposit on the coil surface. The word frost in this study refers to the formation of ice crystals in air or on surfaces, either by freezing of a dew droplet or by a phase change from water vapor to ice directly. Frost deposition on the walls of cold storage freezers and evaporator coil is usually undesirable. The main problems associated with frost growth on an evaporator coil are the decline in heat exchanger efficiency resulting from an insulating effect of the frost layer and the rising pressure drop due to a decreasing hydraulic diameter of the flow channel, which in return increases the energy consumption of the air-blowing fan. While, in cold storage freezers products quality suffers as frost forms on the product while in the freezer. For these reasons frost must be removed be means of defrost for restoring the coil performance or chipped away manually form the walls and product in cold storage freezers. The physical structure of the frost layer forming on an evaporator coil depends on many factors, including the evaporator coil design and its operating temperature, entering air dry-bulb temperature and relative humidity, and the face velocity of the air entering the coil, Şahin [1]. The first regime of frost formation over cold wall was characterized by Dietenberger [2] as follows: the initial frost layer can begin in one of two ways. In the first case, initial condensation occurs at nucleation sites on the wall resulting from a critical supersaturation. In the other case (*i.e.* for a very cold wall), boundary layer fogging occurs and the fog becomes the major source for water droplet condensation on the wall. For cooling of moist air at freezer temperatures, Smith [3] proposed a concept of frost formation in accordance with a graphic plot on a psychrometric chart. The concept suggests that when the line representing the temperature and absolute humidity of the air crosses the saturation curve of the psychrometric chart (*i.e.* becomes supersaturated) the unfavorable frost formation occurs. Once a supersaturated state exists in air, whose temperature below the freezing point, fog and ice fog is likely to form based on operating temperatures. This formed frost under supersaturated condition has affinity to deposit on any surface in their path inside the freezer. In addition, it is snow-like with low density; consequently have low thermal conductivity (more insulating). When it is deposited over evaporator coil it have higher impact on coil airflow rate reduction, and need more energy to defrost than frost formed under less extreme conditions. A symptom of such frost when formed on evaporator coil is that the coil performance deteriorates extremely rapidly and coils seemingly require near-continuous defrosting. Smith [4] discussed his concept [3] of applied psychrometrics in typical industrial freezers issues

* Tel.: +20 0 88 2411146; fax: +20 0 88 2332553.
E-mail address: ah-hamza@aun.edu.eg

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doi:10.1016/j.enconman.2009.02.007

Nomenclature

Alphabetic symbols

a, b and c	coefficient in Eq. (2)
D	demarcation condition, –
p	partial pressure, Pa
P	total pressure, Pa
RH	relative humidity, %
T	temperature, °C
UA	total conductivity, W/°C
W	humidity ratio, kg_{H2O}/kg_{da}

Subscripts

a	air
cs	coil surface
$critical$	critical
da	dry air
DB	dry bulb
dry	dry
fr	frost
H_2O	water vapor
ice	ice
in	entering
$load$	load
out	leaving
ref	refrigerant
s	saturation
scw	supercooled water
sw	saturated water

pertaining to latent heat, equipment-related loads. Sherif et al. [5], Mago and Sherif [6], and, Cleland and O'Hagan [7] confirmed experimentally Smith [3] concept by using real size evaporator coil.

Throughout the literature, it is clearly observable that very little research (Smith, Sherif and coworkers, and, Cleland and coworkers) has investigated the demarcation boundary for frost formation, inside cold storage freezers or real size evaporator coil, in either subsaturated or supersaturated regions with the aid of the psychrometric chart. In addition, Cleland and O'Hagan [7] published the only available formula in literature, for delineation of the demarcation criteria that declare whether frost is formed in supersaturated and subsaturated regions, based on Smith [3] concept. They used the definition of a critical load sensible heat ratio (SHR), and, they reported that if the actual heat loads have a SHR, less than the critical value then unfavorable frost is likely to occur. Cleland [8,9] used this demarcation criterion to explore aspects of refrigerated facility design and operation, and, to consider the effect of infiltration air into a frozen warehouse and loading dock, respectively. Cleland and O'Hagan [7] reported that the data used are not of sufficient quality to either fully prove or disprove the proposed transition between frost types.

In case of an evaporator coil, to estimate the time and energy required to melt down the formed frost layer (defrost), frost characteristic that is based on whether it formed in psychrometric-subsaturated or supersaturated regions can be helpful to the operator as the frost formation condition characterizes both the frost density and thermal conductivity. For cold storage freezers, prediction of the frost formation type guides refrigerating system designers in their quest for improved designs and efficient operation. Therefore, in this study, a direct formula to predict the demarcation boundaries in psychrometric saturation for delineation the frost formation on cold walls is presented. It declares whether the frost is formed in psychrometric-subsaturated or supersaturated regions. The formula uses the data of the entering air dry-bulb temperature and absolute humidity and the absolute humidity of the air at saturation correspondence to the coil surface temperature. Case studies from experimental measurements as well as measured data from literature are used to validate the formula. Subsequently, characteristics of the frost formed on the cold walls for the studied cases are described.

2. Analysis

To formulate the demarcation boundaries in psychrometric chart to declare whether frost formed in psychrometric-subsaturated or supersaturated regions, to delineate the frost type formed on cold walls, using Smith [3] concept, the following premises are applied on psychrometric chart.

- A straight-line path describes the air-cooling process, line (C–D) in subsaturation or line (A–D) in supersaturated case as shown in Fig. 1 is plotted on the psychrometric chart. The beginning of the path line is the entering air condition, while, the end-point of the path line is coil surface temperature or cold storage freezer temperature and lies on the psychrometric-saturation curve. In this step, the straight-line approximation approach of Stoecker [10] and ASHRAE [11] for cooling and dehumidification through a coil that relates the change in conditions of the air passing the cooling coil is used.
- The demarcation from subsaturated to supersaturated regions, critical condition, and lay at minimum coil refrigeration temperature corresponds to the lowest coil surface temperature that can occur without causing the straight-line path to invade the supersaturated region of the chart. In the premise, line (B–D) in Fig. 1 is plotted tangential to the psychrometric-saturation curve at the coil surface temperature or cold storage freezer temperature.
- If the air path invades the supersaturated region, the case of line (A–D) in Fig. 1, frost precipitation occurs within the airstream and deposited on the cold walls in their path. Where the path does not invade the supersaturated region (*e.g.* the case of line C–D in Fig. 1 the coil-frost is of ice-like quality and formed over the cold walls.

The following points should be addressed with the premises plotted in Fig. 1. The refrigerant evaporation temperature, T_{ref}, can be occasionally used instead of coil surface temperature, T_{cs} (*i.e.* point D' in Fig. 1). Indeed, using T_{ref} is represents a minimum border for T_{cs} and will lead to conservative estimates of the demarcation boundaries as frost is formed in the supersaturation region. Another point is, in case of evaporator coil as the time passes frost layer thickness increases, consequently, the frost surface temperature increases that is should be used as the end-point of the straight-line approach on psychrometric-saturation curve, point D'' in Fig. 1. In this case, the condition for frost formation shifted the demarcation boundaries slightly into subsaturated region.

To alter the graphic concept into a formula, an equation relating the air absolute humidity at saturation condition with air dry-bulb temperature, psychrometrics saturation curve, is required. The absolute humidity at saturation, $W_s(T_a)$, as function of the air dry-bulb temperature is calculated from ASHRAE [12] by: