Energy and Buildings 86 (2015) 243–256

Contents lists available at ScienceDirect

Energy and Buildings

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

A new theoretical formulation of dew point temperatures applicable for comfort air-cooling systems

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ARTICLE INFO

Article history:
Received 18 April 2014
Received in revised form 10 October 2014
Accepted 14 October 2014
Available online 23 October 2014

Keywords:
Psychrometry
Dew point temperature
Air conditioning
Wet bulb temperature
Cooling coil

ABSTRACT

Dew point temperature (DPT) of moist air plays a key role in ascertaining the comfort condition as well as indoor air quality for built environments. This article outlines a simple method to transform the fundamental relation between saturation pressure and temperature into a concise mathematical form for dew point temperatures of moist air that is applicable for normal comfort air conditioning systems. The error between the results from the derived equation and the ASHRAE correlation is found to be well within the accuracy limits of commonly used climatic sensors. Based on this equation, a simple computational method for wet bulb temperature (WBT) is proposed. The results from this method show minuscule error in comparison with the standard psychrometric data. Also, the DPT equation is used as a basis for plotting wet sensible and latent loads of a cooling dehumidifying coil by applying both temperature and humidity discretization schemes. Application of the inherently simple and aptly accurate DPT equation results in the representation of subtle variations in coil loads at varying psychrometric parameters of moist air, to be conclusive and theoretically conformal.

1. Introduction

Psychrometry finds its direct application in meteorology, agricultural engineering, food processing and air conditioning science. A comprehensive knowledge of thermodynamic properties of moist air enables engineers and practitioners to make decisions for the optimum performance of their systems. Specially made psychrometric charts and data tables are readily available for determining the associated properties of moist air at a given condition. However, most of these data are at sea level ambient pressure and a generalized application may lead to erroneous results. Hence, computer programs or calculation spreadsheets are viable options for solving the complicated psychrometric equations and acquiring the correct data relevant to the system in question. Nevertheless, simplification in correlating the psychrometric properties of air allows simple analyses of systems and related components from a theoretical as well as practical point of view.

Various correlations have been used extensively over years for the determination of moist air properties. Some of these include Magnus' formula [1], Goff–Gratch formulation [2], Arden Buck formula [3], Hyland–Wexler correlation [4], ITS-90 formulation [5] etc. The model developed by Wexler et al. allows the computation of moist air properties in a temperature range of 0–200 °C. In recent years, Hermann et al. [6] developed a modified Wexler model for moist air that is valid for a temperature and pressure range of 130–623.15 K and 0.01–10 MPa respectively. Both of these models have considered dry air and water vapor as real gases and incorporated cross virial coefficients for accurately determining the moist air properties. In addition, a vapor-pressure enhancement factor has also been included in these methodologies that account for an increase in saturation vapor pressure of water in moist air at elevated total pressures [4,6]. All of these considerations have made the final equations and associated calculations highly complex and intricate. To enhance the computational efficiency of psychrometric calculations, Rogdakis et al. [7] has proposed a simple model based on appropriate polynomial correlations of higher or lower grades depending on the required level of accuracy. Nevertheless, the approximate form obtained from this model cannot avoid all the intricacies.

Generally, for air conditioning, the moist air can be considered as a perfect gas. As per ASHRAE fundamentals handbook, this assumption results in manageable errors for moist air properties that reduce with a decrease in barometric pressures [8]. Furthermore, for the ambient pressures encountered in air conditioning applications, the enhancement factor correction is negligible [9]. These assumptions provide an allowable trade-off between

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http://dx.doi.org/10.1016/j.enbuild.2014.10.029
0378-7788/

Nomenclature

Symbols used

C_p	specific heat capacity of moist air (kJ kg^{-1} K^{-1})
C_{pa}	specific heat capacity of dry air = 1.006 kJ kg^{-1} K^{-1} (0.24 Btu lb^{-1} °F^{-1})
C_{pl}	specific heat capacity of liquid water = 4.186 kJ kg^{-1} K^{-1} (1 Btu lb^{-1} °F^{-1})
C_{pv}	specific heat capacity of water vapor = 1.86 kJ kg^{-1} K^{-1} (0.44 Btu lb^{-1} °F^{-1})
ΔC_{plv}	difference of specific heats of liquid and vapor: 2.326 kJ kg^{-1} K^{-1} (0.56 Btu lb^{-1} °F^{-1})
DPD	dew point depression (K)
l_0	specific latent heat of vaporization at 273 K = 2501 kJ kg^{-1} (1075 Btu lb^{-1})
$\dot{m}_a$	total mass flow rate of air (kg s^{-1})
P	saturation pressure (kPa)
P_t	ambient pressure (kPa)
$\dot{Q}$	coil load capacity (kW)
q	specific enthalpy change across a coil (kJ kg^{-1})
R	gas constant for water vapor = 0.4618 kJ kg^{-1} K^{-1} (0.1 Btu lb^{-1} °F^{-1})
RH	relative humidity (%)
T	absolute temperature (K)
T_d	dew point temperature (K)
WBT	wet bulb temperature (K)
WBD	wet bulb depression (K)

Greek symbols

α	ratio of molecular mass of water vapor to dry air (=0.622)
ω	humidity ratio (kg moisture/kg dry air)

Subscripts

0	reference state 273.15 K
in (or 1)	AHU inlet condition
out	coil outlet at ADP condition
dpt	coil inlet dew point condition
lat	latent part of coil load
sen	sensible part of coil load
sen-dry	sensible part of load capacity for a dry coil
sen-wet	sensible part of load capacity for a wet coil
wb	at wet bulb temperature

simplicity and accuracy in the theoretical formulations of the moist air properties, which are applicable for various air conditioning problems and cases.

A systematic procedure for the determination of all psychrometric properties of moist air has been discussed extensively in literature [10–13]. Furthermore, preparation of generalized psychrometric charts based on composite properties has been a subject of consideration [14]. Psychrometric analysis may take various forms depending on the application and objective. Psychrometric charts are traditionally used to represent and examine various air conditioning systems and processes. Architects and engineers employ these charts for bioclimatic designs [15,16], comfort analysis [17,18] and metrological studies [19,20]. Furthermore, psychrometric computations are extensively applied for analyzing and evaluating the response of various systems at varying operating parameters. Addressing this point, the research conducted in recent years on innovative evaporative cooling technology [21–23], drying and desalination process [24–26], desiccant dehumidification techniques [27,28] and thermodynamic analyses of air conditioning design problems [29–33] are worth mentioning.

In spite of the extensive application of psychrometry in diverse fields of engineering, its utility is seemingly restricted to the determination of moist air properties at various thermodynamic state points of the involved process. Scarcely, the equations or the relations are actually applied for parameterizing the process itself and modeling it exclusively in the purview of basic thermodynamic and mathematical principles. This article aims at bridging that gap.

The primary objective here is to show a simple theoretical formulation of dew point temperature (DPT) appropriate for comfort cooling systems. The relationship expressed by the Clausius–Clapeyron equation is the main underlying mathematical principle for achieving this objective. Even though this equation is well known, it has not been applied extensively for air conditioning studies or for the determination of psychrometric properties of moist air. The ASHRAE correlation that is valid for DPT between 0 and 93 °C [8] is taken as a baseline for comparison with the derived equation. However, the scope of this article is limited exclusively to chilled water systems that represent a large part of air conditioning systems used worldwide. Having established a simple equation for DPT, the subject matter is extended for computing air wet bulb temperatures (WBT) and chilled water coil loads by applying numerical iteration and discrete summation methods respectively.

In totality, the purpose and contribution of the present work can be surmised as:

- Formulating an accurate and usable equation for dew point temperatures of moist air by bringing together the basic principles of thermodynamics.
- Applying the derived equation in a theoretical framework to develop novel techniques for determining wet bulb temperatures and wet coil loads (sensible and latent), which are basic design requirements for comfort air conditioning applications.

2. Dew point formulation

Out of all the practical applications of psychrometry, air conditioning deals with a very specific and probably the most limited temperature band. This is due to either weather conditions or constraints on the equipment side for maintaining proper comfort conditions to the occupants in the zone. Table 1 shows the temperature ranges that are prevalent in air conditioning system design based on the extreme weather conditions recorded around the globe and the thermal limits for the equipment [34–39].

On a psychrometric chart, a design region (ABCDE) can be obtained by enclosing the boundaries of these climatic conditions (refer to Fig. 1). Any ambient (or equipment inlet) condition that falls outside this region is either not recorded till date or a cooling and dehumidification process alone cannot bring it to a suitable supply condition that can provide comfort cooling to the conditioned space. For example, ambient conditions inside region BB′C′C require either steam injection (for cold and dry) or evaporative cooling (for hot dry), to sufficiently humidify the air prior to supplying into the space. For such a relatively limited operational range, approximate psychrometric properties based on the ideal gas assumption for moist air provide satisfactory compliance.

Table 1
Specific limits to ambient and system design conditions.

Application/specifics	Applicable temperatures	Ref.
Extreme ambient DBT	57.7 °C	[34–36]
Extreme ambient DPT	35 °C	[35,36]
Extreme ambient WBT	36.2 °C	[35]
Zone DPT prescribed for comfort	<16.8 °C (12.8 °C for hot-humid climates)	[37,38]
Typical ADP for chilled water coils	≥4 °C	[39]