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METHOD FOR SIMULATION OF THE PERFORMANCE OF AIR-CONDITIONING SYSTEMS SERVING INTERIOR BUILDING ZONES

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ABSTRACT

This article presents a simulation method for predicting the long-term energy performance of a central air-conditioning system serving interior zones of buildings with similar daily cooling load profiles. The method is based on a multiple psychrometric analysis of the system, frequency-based climate model, and a measured daily cooling load profile. Comparison with existing simulation software is discussed.

INTRODUCTION

The prediction of long-term energy performance of existing air-conditioning systems is a common task when conducting energy retrofit programs. For example, upgrade of an air-conditioning system with economizer control provides electricity savings through the replacement of mechanical cooling with outdoor air. However, for some applications requiring a certain indoor humidity level, increased volume of outdoor air supply increases steam consumption by the humidifier. Therefore, analysis based on simulation of the whole system, including the controls sequence, is required to determine the net energy savings.

A simulation model is also often required for verification of energy retrofit performance (ASHRAE, 2000, International Performance Measurement and Verification Protocol, 2000). As per recommendations of the references, verification should include direct measurement of key characteristics.

Use of the existing simulation models such as DOE computer programs, TRNSYS and others may be difficult for a number of reasons:

- Time-based approach of the existing algorithms calculating hour-by-hour cooling loads involves input of building data that may not be available (structural properties, rate of internal heat gains, etc)
- Cooling loads calculated by the program algorithm cannot be specified directly when the measured data is available
- Extensive input results in high cost of simulation
- Temperature and humidity trends are difficult to use in the enthalpy analysis of air-conditioning systems.

The cooling load calculation algorithms in these existing programs may generate significant uncertainty. In order to reduce the uncertainty and simplify calculations, the proposed method is based on the concept that daily cooling load profiles in the interior zones of buildings are similar over the year.

A daily cooling load profile can be measured over a short-term period and then applied over an entire year. If the measurements are not feasible, the profile can be specified based on the measurements done for buildings with similar occupancy and use. This concept corresponds to the Transfer Function method described in ASHRAE Handbook, 1997 and Design Load User's Manual for the Hourly Analysis Program, 1994. The first reference formulates that, for a specific room, the cooling load pattern for a specific type of heat gain will always be the same. The total cooling load of the room is found by superposition of the cooling loads from all heat gain sources. Therefore, at regular activity levels in the building, the daily cooling loads should have identical profiles throughout year.

The concept creates an opportunity to develop a simplified "static" model for simulation as an alternative to the existing dynamic models.

CLIMATE MODELING

Existing climate models (for example, TMY model in ASHRAE Handbook, 1997) generate time-based curves of the weather data necessary to calculate time-dependent building loads.

The proposed model, based on a pre-determined daily cooling load pattern, does not require a series of hour-by-hour weather data. For this reason, yearly frequencies of the outdoor air temperatures for each of 24 hours of the day can be determined from meteorological data. The term frequency here means a cumulative occurrence of a certain outdoor temperature bin (for example, temperatures in the range of 20+/-1°C) within one year.

Similar to the existing bin-method (ASHRAE Handbook, 1997), this approach uses bin-temperatures and the associated frequencies to calculate the air-conditioning system performance.

A graphical representation of ambient temperature frequency distribution for Toronto area is shown in Figure 1 for different times of the day.

Wet-bulb temperatures occurring at 0:00, 1:00 … 23:00 hours within the same time-domain were used to determine their correlation with the dry-bulb temperatures at different times of day. For example, the correlation curve at 13:00h is the following:

$$WB= - 0.0022 \times DB^2 + 1.029\, DB - 2.1796 \qquad (1)$$

Analysis of all 24 regression curves reveals a statistically sound correlation (coefficient R^2 is greater than 0.96).

Thus, the developed climate model represents two two-dimensional arrays of: *Frequency(DB, Time of the day)* and *Wet-bulb temperature(DB, Time of the day)*. Each array has the same arguments: DB-equidistant representative dry-bulb temperatures (min, -22oC, -20oC, -16oC, …38oC, max) and hours of the day (0:00, 1:00, 2:00,…23:00h).

MODELING OF THE COOLING LOAD

Cooling load profiles of the internal zones are driven primarily by the internal heat gains. Regularity of these heat gains makes it reasonable to assume similarity of daily cooling load profiles throughout the year and, hence, reasonable to avoid the use of complicated time-based algorithms ranging from the semi-empirical Transfer Function method to complicated finite-difference solutions of non-linear unsteady differential heat balance equations (for example, Clarke, J. et al., 1990, Lewis, P.T. and Alexander, D.K. 1985, Manassypov R., 1997).

To verify this concept a number of simulations were carried out. A common in commercial practice software HAP-4.10 (Design Load User's Manual for the Hourly Analysis Program, 1994) based on TF method was used to simulate a commercial building with numerous internal zones. Building weight was changed from 140kg/m² to 590kg/m² and the heat gain magnitudes were doubled keeping the same schedules to assess their influence on cooling load profiles. The results for a typical day in July and January are shown in Figure 2.

The simulation demonstrates that cooling load profiles are virtually identical and fluctuate insignificantly throughout the year. The variance of the simulated profiles lies within a 0 to 8% range.

A series of cooling load profiles were also measured in a high-rise office building with 60% glass area. The perimeter zone was served by a central air-conditioning system using terminal induction units. The system compensated for all thermal loads coming through the envelope. The core of the building was served by a variable volume system with terminal reheat coils (Figure 3) supplying 20.9m^3/s of air from 6:00h to 21:00h.

Common supply and return air temperatures and supply fan airflow trends were recorded through an existing digital system over a one-month period in 30-minute increments. During the experiment the supply air temperature was maintained at 13.9oC and the return air temperature fluctuated around 24.4oC.

The reheat coils were disabled during the retrofit, so the cooling load profiles were determined as a function of the instantaneous airflow rate and the supply and return air temperature difference. Some of the measured daily airflow trends are shown in Figure 4 at the start, midpoint and end of the experiment. Taking into account the consistent supply and return temperature difference, they represent similar daily sensible cooling load profiles. The profiles indicate a typical morning cool-down load when the system removes the heat accumulated during the night. People occupied the served area gradually from 7:00h and started to leave the building at 17:00h. This is indicated by the profile that ramps up at approximately 8:00h and down at 6:00h.

It should be noted that the measured profiles reflect the net effect generated by both the heat gains and the "non-ideal" system operation when the system output may be not quite equal to the load.

The series of actual daily cooling load profiles can be replaced by a normalized representative profile without significant loss of accuracy. They are averaged to the normalized fractional cooling load related to the maximum instantaneous load

$$FL= Load/Max\ Load = \varphi\ (Time\ of\ day),\ \% \qquad (2)$$

This normalized profile can be used to predict the energy performance of air-conditioning system over the whole year.

MODELING OF THE SYSTEM OPERATION

An air-conditioning system is considered as a perfectly insulated airflow circuit gaining or losing thermal energy and humidity through a number of heat-and mass transfer devices (the served zone being one of the "devices"), as shown in Figure 3. The VAV box on the schematic represents all individual VAV boxes and responds to the sum of coincident cooling loads of the served zones represented by formula (2).

The control system responds to the driving variables of ambient temperature and humidity ratio and the building loads. It maintains airflow characteristics in the designated points of the circuit (For example, in point S) based on a specified sequence and pre-determined set points.

Other points in the circuit have no fixed conditions (For example, point M). In this case, the algorithm manipulates steady state equations of the heat and humidity balances between the circuit, environment and the served zone and graphical methods of the psychrometric analysis to determine coincident transient airflow conditions in "uncontrolled" points of the circuit. The steady state term here means that net heat and humidity gain of the air circuit volume is considered zero in any given moment. The assumption neglects specific heat and humidity capacities of the air circuit. It also assumes that output of the system elements is equal to the controlled load.

The algorithm uses common thermodynamic equations of moist air properties to calculate humidity ratio, relative humidity, enthalpy and density in air-conditioning system for each of the 24-hours of a day for every bin- temperature of the climate model at a given atmospheric pressure. It generates about 480 psychrometric data sets representing discrete performances of the air-conditioning system throughout the year based on a specified control sequence. These data sets are available for animation of the associated psychrometric charts and visual analysis.

The algorithm calculates enthalpies upstream and downstream a system element to define its energy performance associated with a certain climate and indoor conditions. The frequency is used to calculate yearly consumption of this element.

The chart in Figure 5 presents the calculated yearly trends of air conditions in some points of the air circuit. For example, the continuous bold line indicates the outside air condition change from the maximum temperature in summer to the minimum temperature in winter (point O in Figure 3).

The discontinuous dotted line determines the associated conditions of the indoor air (point I) within the year.

The discontinuous dashed line indicates the drive of air conditions in the mixing section of the air-handler (point M in Figure 3) throughout the year.

The formulas of the algorithm are trivial and are not attached here.

RESULTS

In order to approbate the proposed method, the method algorithm was coded using MS Visual Basics resources. A test simulation was run for an air-conditioning system serving a building in Toronto. The system was configured as shown in Figure 3. It supplied 37.8 m^3/s at 13.9°C. The control system provided 24.4°C and 30% relative humidity of indoor air.

A portion of the simulation results, shown in Table 1, illustrates the air circuit characteristics at outdoor temperature 35.6°C occurring at 13:00h, where HR refers to humidity ratio. The point tags correspond to the points shown in Figure 3.

The psychrometric chart shown in Figure 6 visualizes the results in Table 1. The hatched area covers the climate domain. The upper curve with higher humidity level corresponds to 0:00h, and the lower curve corresponds to 13:00h. The curves indicating other times of the day are distributed correspondingly inside the hatched area. Every point on each curve has an associated frequency, providing a virtually 3-dimensional picture of this climate model.

It should be noted that the distribution of the curves reveals a tendency for symmetrical humidity ratio increase from noon toward the night throughout the whole year. This ensures that calculation of wet-bulb temperatures based on the statistical time-of-day analysis substantially improves the accuracy of the simulation.

The chart in Figure 6 shows the air treatment at ambient temperature of 35.6°C. For example, line M-C reflects energy performance of the cooling coil. Lines C-S and I-R indicate heat gains from supply and return fans. Graphical analysis is shown to illustrate a means to validate the interim results. It is also useful for transient analysis of controls performance throughout year.

Verification of the proposed simulation algorithm faces many challenges including the following:

- Measurement of numerous variables during a long-term period is very expensive and complex
- Repetition of the same measurement conditions is questionable

- There is no simulation software with accredited accuracy that could be used for testing (Aude, P. et al., 2000, Lomas et al., 1997).

The capacity of the proposed method was evaluated by comparison with simulation by the program HAP-4.10 (Design Load User's Manual for the Hourly Analysis Program and the System Design Load Program, 1994). The test case was a hypothetical constant air volume system delivering 9.9 m^3/s of supply air to the core area of a public library situated in Toronto. The system was retrofitted to a variable air volume system equipped with an integral dry-bulb temperature economizer. Energy savings result from reduction of electricity consumption by the supply and return fans driven by installed variable frequency drives and reduction of the refrigeration load on the cooling coil due to economizer operation.

The testing program used the TMY climate model and the tested algorithm used the developed frequency-based climate model based on 1999 to year 2001 meteorological data. The tested program applied the cooling load patterns generated by HAP-4.10 to exclude a possible influence of thermal mass of the building.

Tables 2 and 3 reveal acceptable correlation of the yearly energy consumptions calculated by the testing and the tested programs.

The deviations are caused by the following reasons:

- Difference in climate models
- Some difference the controls sequences
- The testing program calculates an instant output of the system elements in response to magnitude and duration of the deviation between the controlled variable and its set point. The tested algorithm ignores this deviation.

The comparison indicates that the proposed method is capable of providing reliable results.

CONCLUSION

The developed method is based on multiple psychrometric analysis applied to the air-conditioning system exposed to pre-determined combinations of outdoor and indoor conditions that occur throughout the year with a certain frequency. The method could be categorized as a *static simulation model* to distinguish it from existing dynamic simulation models. It focuses on the air-conditioning system performance as opposed to building performance by utilizing the measured daily cooling load profile, avoiding the input of building data and improving quality of the results.

The method can be successfully used for site verification of energy savings measure performance.

The simulation model can be the basis of a computer program designed for energy analysis of the retrofitted air-conditioning systems serving areas with identical daily cooling loads.

The simplicity of the method and the minimal time requirements for calculations suit the time frame and budgets of engineering companies dealing with HVAC design and energy services.

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NOMENCLATURE

DB - dry-bulb temperature
WB - wet-bulb temperature
FL- fractional cooling load
Load – current cooling load
Max Load – maximum value of daily cooling load profile

Table 1
Performance of the air-conditioning system at 13:00h and outdoor temperature 35.6oC

POINT TAGS IN FIG. 3	**O**		**M**		**C**		**S**		**I**		**R**	
AIR PROPERTIES	DB, °C	WB, °C	DB, °C	HR, g/kg	DB, °C	HR, g/kg	DB, °C	HR, g/kg	DB, °C	HR, g/kg	DB, °C	HR, g/kg
VALUES	35.6	24.6	28.6	10.5	12.2	7.3	13.9	7.3	23.9	7.8	24.4	7.8

Table 2
Simulation of the constant volume system

PERFORMANCE	**BY PROPOSED METHOD**	**BY HAP-4.1**
Energy consumed by supply fan, kWh	489,923	382,871
Energy consumed by return fan, kWh	97,985	98,073
Energy consumed by cooling coil, kWh	809,100	898,796

Table 3
Simulation of the variable volume system

PERFORMANCE	**BY PROPOSED METHOD**	**BY HAP-4.1**
Energy consumed by supply fan, kWh	235,426	276,527
Energy consumed by return fan, kWh	49,048	59,798
Energy consumed by cooling coil, kWh	450,067	576,625

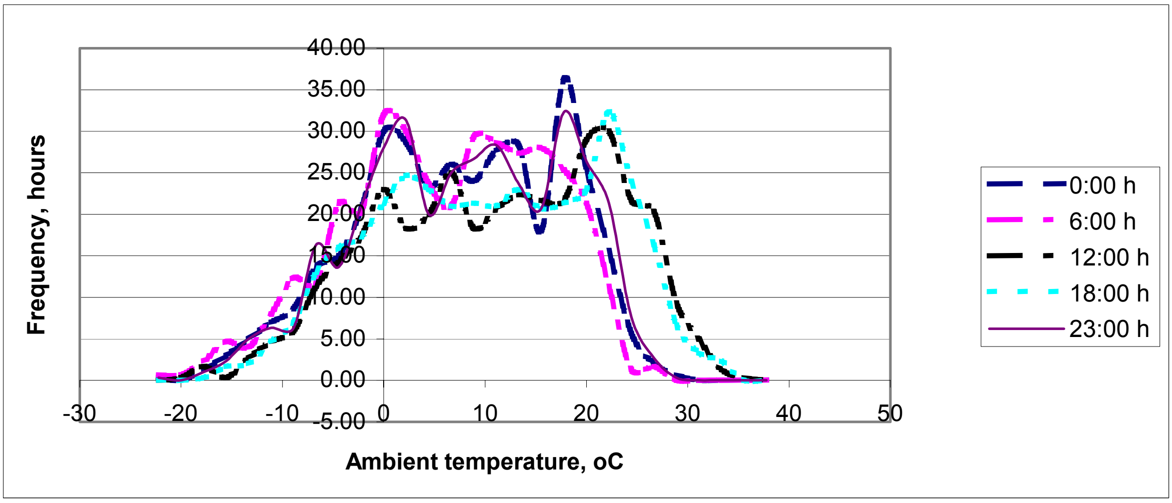

Figure 1 Temperature frequency profiles for Toronto area

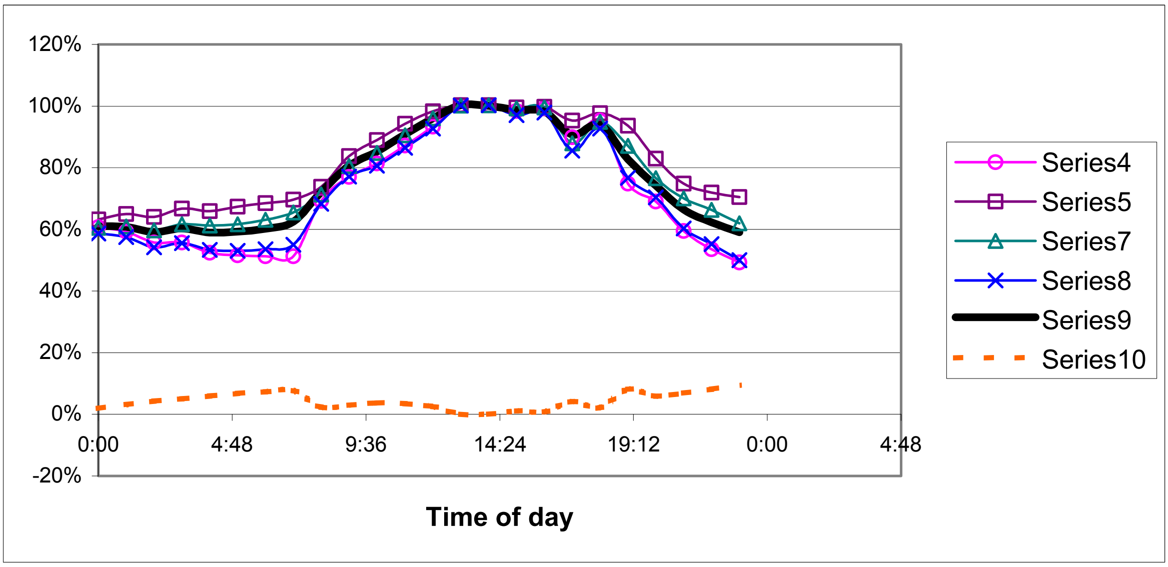

Figure 2 Cooling load profiles in July: S.4 – building weight 140 kg/m²; S.5 - building weight 590 kg/m². Cooling load profiles in January: S.7- building weight 140 kg/m²; S.8- building weight 590 kg/m²; S.9 – average cooling load profile; S.10 – variance of the profiles

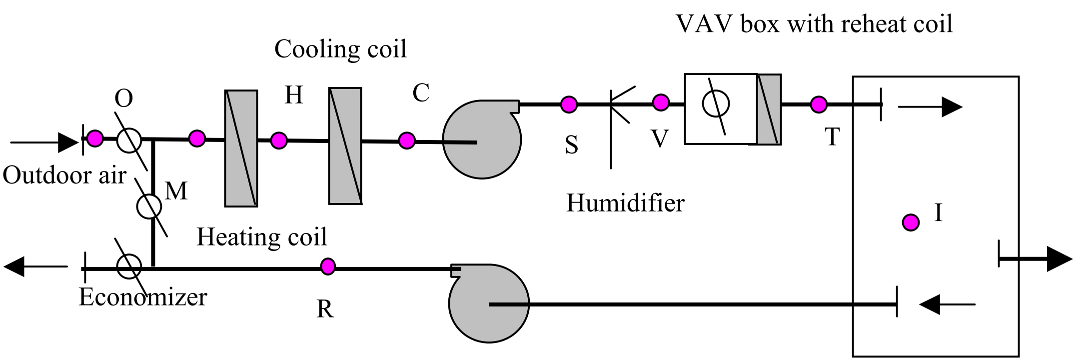

Figure 3 Schematic of the air-conditioning system serving interior zones

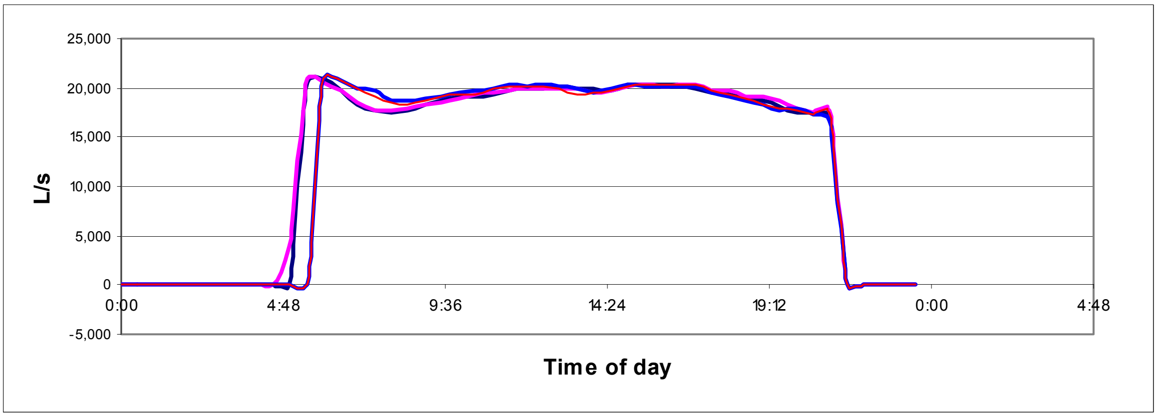

Figure 4 Daily supply airflow trends recorded on August 8th, 15th, 25th and 30th of 2001 year

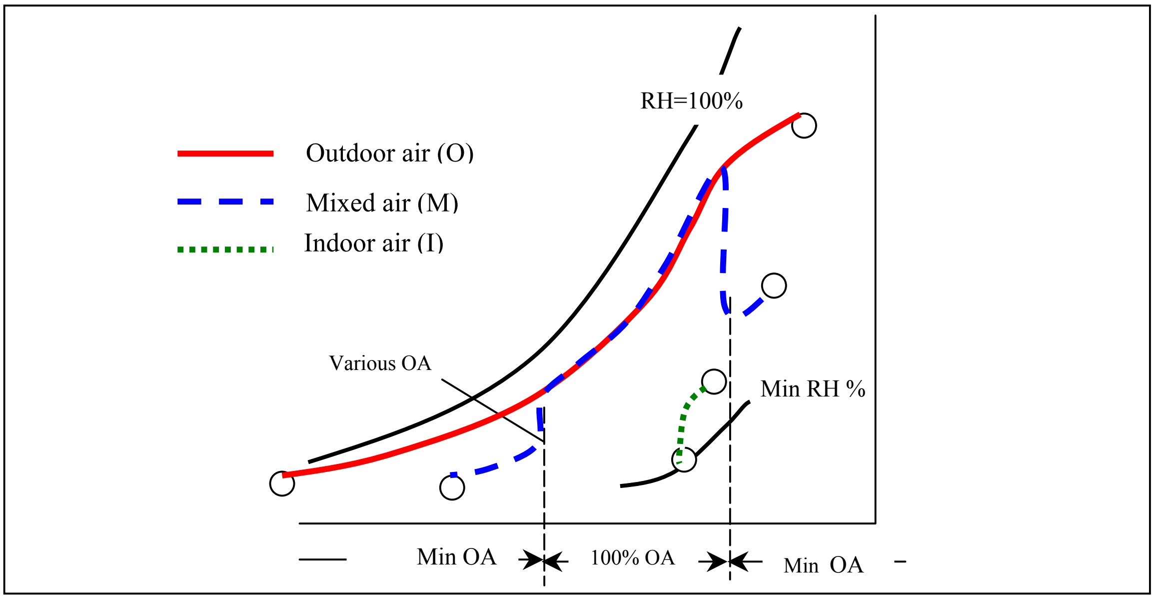

Figure 5 Yearly air condition trends in some points of the system in Figure 3

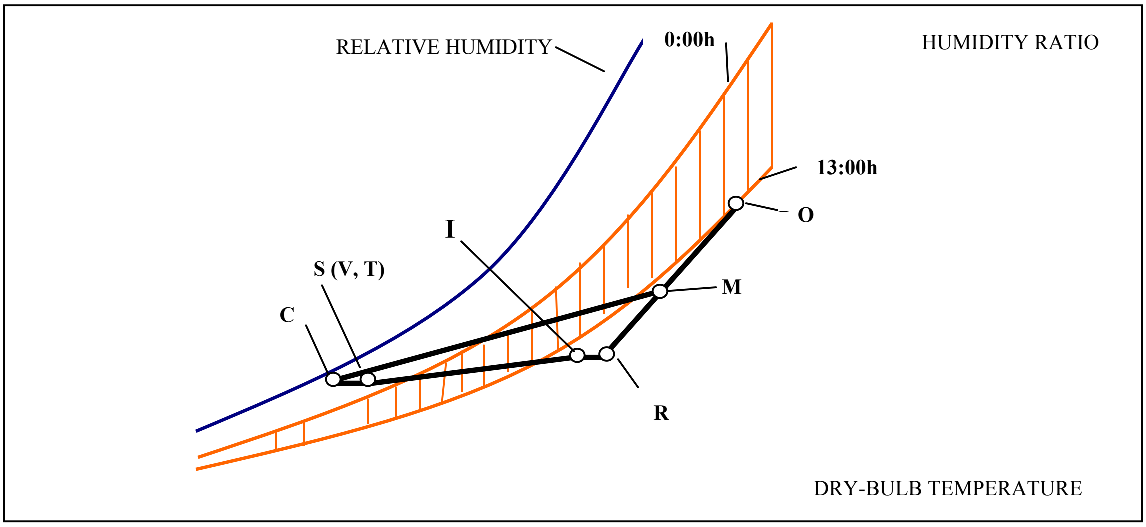

Figure 6 Psychrometric chart of the system operation as per the data from Table 1

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