Discussion on the measures of achieving the sub-wet bulb temperature by evaporative cooling

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Abstract. On the basis of introducing the wet-bulb temperature which is lower than the outdoor air temperature and achieved by the indirect-direct evaporative cooling technology, this paper argues that the sub-wet bulb temperature can be used to characterize the air and water-out state parameters of the equipment, and the sub-wet bulb efficiency can be used to characterize the degree to which such equipment can go below the wet-bulb temperature. Moreover, this paper also introduces the typical equipment of China and foreign countries which uses indirect-direct evaporative cooling technology to achieve the sub-wet bulb temperature. The sub-wet bulb efficiency of the foreign indirect-direct evaporative cooling equipment is 106%. According to test results, the sub-wet bulb efficiency of the indirect-direct evaporative cooling air handling units in China is 117%; the sub-wet bulb efficiency of surface pre-cooling evaporative chillers is 115%, and the sub-wet bulb efficiency of tubular pre-cooling evaporative chillers is 120%. Therefore, the analysis results show that the sub-wet bulb temperature and sub-wet bulb efficiency can be used to directly characterize the air/water-out state parameters of such equipment.

\textbf{Symbol table}

\begin{tabular}{|l|l|}
\hline
\textbf{T:} & temperature, °C \\
\textbf{tw:} & dry-bulb temperature of outdoor air, °C \\
\textbf{tsw:} & wet-bulb temperature of outdoor air, °C \\
\textbf{to:} & air-out temperature, °C \\
\textbf{tin:} & temperature of inlet point, °C \\
\textbf{tout:} & temperature of outlet point, °C \\
\textbf{m:} & mass flow, kg/s \\
\textbf{Q:} & cooling capacity, kW \\
\textbf{c_p:} & specific heat, kJ/kg·°C \\
\textbf{k:} & heat transfer coefficient \\
\textbf{kd:} & mass transfer coefficient \\
\textbf{A:} & heat exchange area, m² \\
\textbf{η_w:} & wet-bulb efficiency \\
\textbf{η_d:} & dew-point efficiency \\
\textbf{η_w:} & water-side efficiency of the packed tower \\
\textbf{η_sub:} & sub-wet bulb efficiency \\
\textbf{r_0:} & latent heat of water vaporization \\
\hline
\end{tabular}

\textbf{Subscript}

\begin{tabular}{|l|l|}
\hline
\textbf{a:} & wet air \\
\textbf{W:} & water \\
\textbf{in:} & water inlet \\
\textbf{out:} & water outlet \\
\hline
\end{tabular}
1. Introduction

The wide application of evaporative cooling technology has great significance for energy saving and emission reduction. At present, various types of equipment produced by evaporative cooling technology have been widely applied in air handling systems of public buildings, including direct evaporative cooling air handling units and chillers, and indirect-direct evaporative cooling air handling units and chillers [1-3]. The direct evaporative cooling process is an isothermal process, and the limit temperature that the direct evaporative cooling equipment can reach by water and air handling is the wet-bulb temperature of the outdoor air. However, due to the limitations of various factors, the limit temperature of the direct evaporative cooling equipment in the actual operation is often higher than the wet-bulb temperature of the outdoor air. Since the air/water-out temperature is affected by the wet-bulb temperature of outdoor air, the applications scope for the direct evaporative cooling equipment is quite small. Therefore, in recent years, evaporative cooling air handling equipment with a lower air/water-out temperature has attracted the attention of many scholars at home and abroad. Moien Farmahini-Farahani et al. found that a system can save energy by 75%-79% by the air inlet of the pre-cooled evaporative cooling equipment [4], and Pietro Finocchiaro et al. concluded that without the assistance of mechanical cooling, a system combining the solar auxiliary equipment with evaporative cooling can make the air-in temperature of the evaporative cooling equipment reach 21-22 °C [5]. The indirect-direct evaporative cooling equipment developed by Xi’an Polytechnic University has produced good application results in practice [6-8]. Ala Hasan et al. provided an analytical solution for regenerative M-cycle cooler and found that evaporative cooling equipment can make the outdoor air below the wet-bulb temperature [9]. However, many papers have not explicitly defined the state point with a temperature (achieved by the evaporative cooling equipment by lowering the outdoor air temperature or handling cold water) which falls between the dew-point temperature and the wet-bulb temperature of outdoor air[10-24]. In this paper, the temperature of this state point is called the “sub-wet bulb temperature”.

2. Interpretation of the sub-wet bulb temperature and efficiency

An indirect-direct evaporative cooling air handling unit or chiller can process the air-in temperature or water-out temperature into a state point with a temperature lower than wet-bulb temperature of outdoor air and higher than the dew-point temperature and the temperature of this state point is defined as the sub-wet bulb temperature. Figure 1 is the psychometric chart for the process in which the indirect-direct evaporative chiller produces cold air/water. The air in the outdoor state of W is cooled to the state of W1; the air in the W1 point has a countercurrent heat and mass transfer with the spray water, making the water temperature approach from the t_in point to the t_out point. After the heat and mass transfer is fully performed, theoretically, high-temperature cold water with a temperature close to $t_{sw1}$ can be produced. As can be seen from the figure, the temperature $t_{out}$ of the high-temperature cold water falls between the outdoor air wet-bulb temperature $t_{w}$ and the dew-point temperature $t_{d}$. In other words, the temperature $t_{out}$ is the sub-wet bulb temperature. In a similar way, after a full heat and mass transfer, indirect-direct evaporative cooling air handling units reach an air-in temperature of $t_{sw1}$. The sub-wet bulb temperature is a state point with an air-in temperature of $t_{sw1}$ and a state point with a water-out temperature of $t_{out}$.

The Formula (1) is usually used to calculate the efficiency of direct evaporative coolers or direct evaporative cooling air handling units, while the Formula (2) is usually used to calculate the efficiency of indirect evaporative coolers or indirect evaporative cooling air handling units. The cold air or water produced by the indirect-direct evaporative cooling air-conditioning technology is simultaneously subject to the equal-wetting process and the isothermal process, and it is improper to use the wet-bulb efficiency or the dew-point efficiency to evaluate the indirect-direct evaporative cooling air-conditioning unit or the chiller. Therefore, no consensus has been made on which formulas can be used to calculate the efficiency of indirect-direct evaporative cooling air handling units and indirect-direct evaporative chillers. Formula (3) for the water-side efficiency of the direct evaporative cooling module in cold water is given in Literature [8] and Literature [15]. This formula can reflect the
efficiency of the evaporative cooling chiller from one side. However, in Formula (3), \( t_{sw1} \) is the wet-bulb temperature of the inlet air in the direct evaporative cooling module, that is, the wet bulb temperature of the air precooled by the indirect evaporative cooling section. Most researchers are concerned about the efficiency of the unit under a fixed outdoor air parameter design condition and the relationship between its air/water-out temperature and outdoor air state parameters. Therefore, based on the definition of the sub-wet bulb temperature, this paper uses the Formula (4) to characterize the efficiency that indirect-direct evaporative cooling technology can achieve.

\[
\eta_s = \frac{t_s - t_0}{t_s - t_{sw}} \times 100\%
\]

\[
\eta_l = \frac{t_v - t_0}{t_v - t_L} \times 100\% 
\]

\[
\eta_w = \frac{t_s - t_{out}}{t_s - t_{sw}} \times 100\%
\]

\[
\eta_{sub} = \frac{t_v - t_{out}}{t_v - t_{sw}} \times 100\%
\]

3. Measures of achieving the sub-wet bulb temperature by evaporative cooling

3.1. Air-cooling evaporative equipment

At present, some foreign scholars have developed the indirect evaporative cooling equipment shown in Figure 2 and Figure 3 to reach the sub-wet bulb temperature which comes close to the dew-point temperature. According to the working principle in Figure 2, the primary air (product air) flows through the dry passage, while the secondary air (working air) flows through the wet passage. The secondary air is a part of the primary air which passes through the small hole of the secondary air passageway and becomes the secondary air. Water films exist on the surface of the wet passage, and the sensible heat of the primary air is absorbed due to the evaporation cooling of the water films. As a result, with its temperature lowered, the primary air is sent to the desired place, while the secondary air is humidified and discharged to the outside. Compared with other forms of equipment, such equipment has higher sub-wet bulb efficiency. According to Literature [25], its sub-wet bulb efficiency can reach 144%, and its equipment volume is relatively small.

Figure 3 is a schematic diagram of how counter-flow indirect evaporative cooling equipment developed by Ala Hasan et al. [9] a sub-wet bulb temperature by a realistic supply air temperature. Such
equipment has no hole between its wet passage and dry passage. Instead, a part of the pre-cooled air at the end of the primary air passageway (that is, dry passage) flows to the secondary air passage (wet passage) and appears as the secondary air. The water film of the secondary air passageway absorbs the sensible heat of the primary air due to the principle of evaporative cooling. The primary air is sent to the desired place, while the secondary air is humidified and discharged to the outside. This can avoid the clogging of small holes caused by the poor water quality and air quality, which may further affect the performance of the equipment. Furthermore, the equipment can be connected in series to reach a sub-wet bulb temperature approaching the dew point temperature [26].

Figure 4 shows a system proposed by Moien Farmahini-Farahani et al. [4], which pre-cools the indirect-direct two-stage evaporative cooling air handling unit by night cold accumulation to reach a sub-wet bulb temperature by air supply. With the help of this system, the temperature dropped to 24.2°C in the town of Tabas, Iran, 20.1°C in Awaz, a southeastern city of Iran, 20.6°C in Kerman, and 20.2°C in Tehran.

Figure 5 is a diagram about the temperature drop effect of the system applied in the town of Tabas, Iran [4]. According to Figure 5, the air-out temperature of the system falls between 13-17 °C. In the literature, Moien Farmahini-Farahani et al. [4] also concluded that this system has efficiency, which is 9% higher than that of the traditional two-stage indirect-direct evaporative cooling system. The energy efficiency ratio of the system is 48.8-58.8, and the sub-wet bulb efficiency of the system is 106%.

Figure 6 is a schematic diagram of the structure of a two-stage evaporative cooling air handling unit which consists of an indirect evaporative cooling section and a direct evaporative cooling section. A tubular indirect evaporative cooler or a plate-fin can be used for the indirect evaporative cooling section.

Figure 7 is a picture of a three-stage evaporative cooling air handling unit which is jointly developed by Xi’an Polytechnic University and a company in Xi’an, on the basis of a tubular indirect evaporative cooler and a direct evaporative cooler. The unit is applied to an office building in Xinjiang. The outdoor air-in dry-bulb temperature $t_g$ of the unit is 32.7°C; the corresponding wet-bulb temperature $t_s$ is 16.5°C; the relative humidity $\Phi$ is 27%; the air-out dry-bulb temperature of the direct evaporative cooling air supply section $t_g$ is 13.7°C; the corresponding wet-bulb temperature $t_s$ is 12.5°C and the relative humidity $\Phi$ is 89%.

Figure 8 shows the relationship between the air-out temperature and the measured outdoor air dry and wet bulb temperature. As can be seen from the figure, the cold air sub-wet bulb temperature that this equipment can reach is 13.7 °C, which is lower than 16.5 °C, the outdoor air wet-bulb temperature. And its sub-wet bulb efficiency is 117%.

![Figure 2. Dew-point evaporative cooler.](image1)

![Figure 3. Counter-flow evaporative cooler.](image2)
Figure 4. Regenerative pre-cooling indirect-direct evaporative cooler.

Figure 5. Simulated data.

Figure 6. Schematic diagram of the indirect-direct evaporative cooling air handling unit.

Figure 7. Picture of the indirect-direct evaporative cooling air handling unit.
Figure 8. Measured data.

All the above-mentioned types of equipment use the dry air energy of the outdoor air and have different passageways, to lower the temperature of the inlet air by using additional secondary air or water or taking away the sensible heat of the primary air through a heat and mass transfer in the secondary passage, thus achieving the goal of cooling. Combining heat recovery technology with direct evaporative cooling technology, we can not only improve the heat transfer efficiency of the heat recovery unit, but also effectively utilizes the energy in the indoor exhaust air. Xi’an Polytechnic University and a company in Nantong have worked together to develop a sensible heat runner-filler air handling unit. The working principle of the unit is shown in Figure 9 [27]. Figure 10 is a schematic diagram of the runner-direct evaporative cooling air handling unit. The working principle of the unit is as follows. In the summer, the outdoor air has a heat and mass transfer with the indoor return air pre-cooled by direct evaporative cooling, and is then further lowered to a sub-wet bulb temperature through an isentropic humidification in the direct evaporative cooling section. A direct evaporative cooling section is added to the indoor return air side, precisely for further lowering the temperature of the return air. The relative humidity of the indoor return air is not 100%, so cooling can be further performed through direct evaporative cooling. Therefore, after the direct cooling, this unit uses a sensible heat runner to pre-cool the outdoor air inletting at the other side, so as to improve the heat exchange efficiency of the runner. According to test results, the average outdoor air dry-bulb temperature of the unit is 30.6 °C and the corresponding wet-bulb temperature is 25.9 °C; and the average temperature drop of the unit is 7.9 °C. And according to calculation results, the efficiency of the runner in the indirect evaporative cooling section is 86.6%; the efficiency of the primary air-side packing section is 53.9%; the air-out temperature is 22.7 °C, which is 2.2 °C lower than the outdoor air wet-bulb temperature of 2.2 °C; and the sub-wet bulb efficiency of the unit is 168%.

Thus it can be seen that the sub-wet bulb efficiency of the runner-direct evaporative cooling air handling unit is higher than that of the tubular-direct evaporative cooling air handling unit. However, it should be noted that the unit was tested in a high humidity place. According to an analysis on the inlet air parameters, the relative difference between the dry-bulb and wet-bulb temperature is only 4.7 °C. Therefore, this unit has a higher sub-wet bulb efficiency of lowering the air-in temperature to the sub-wet bulb temperature in the high humidity place, compared with places with bigger differences between their wet-bulb and dry-bulb temperature. This unit can achieve good application results, if applied in some places with high sensible heating values. However, this unit has just been developed and produced, and the above data of this unit was measured in an air-conditioner workshop as a limited test site. At present, the measured data about this unit in an actual application site is unavailable. We fully believe that this type of air-conditioning units will enjoy great popularity in the market.
3.2. Water-cooling evaporative equipment

In recent years, the development and application of evaporative cooling chillers (water-cooling evaporative equipment) have attracted more and more attention of professionals[10-24]. The evaporative cooling chillers developed on the basis of evaporative cooling technology include direct evaporative cooling chillers indirect evaporative cooling chillers and indirect-direct evaporative cooling chillers. When evaporative cooling chillers are used to prepare high-temperature cold water for the sub-wet bulb temperature as the high-temperature cold source of the temperature and humidity independent control air-conditioning system in the western region, the driving source of the air-conditioning system is dry air energy instead of electric energy, so evaporative cooling chillers have great potentials of energy saving. Indirect-direct evaporative cooling chillers developed by evaporative cooling technology can be used to produce high-temperature cold water, to bear the terminal sensible heat load in the air-water system. And such chillers have been applied in practical engineering, and have achieved good results.

JARVIS ERIC EDWAR has patented an evaporative cooling chiller for the sub-wet bulb temperature (Patent No.: US20100722741) [28]. This equipment pre-cools the outdoor air by a dew-point heat exchanger. After that, the pre-cooled air flows into the circulating water in the direct evaporative cooling section to achieve the cooling effect. The patent explains in detail how to make the cold water temperature reach the sub-wet bulb temperature.

Figure 11 is a schematic diagram showing the air-water cycle of an indirect-direct evaporative cooling chiller which can produce high-temperature cold water for the sub-wet bulb temperature. The outdoor air is pre-cooled by the air cooler 1 and then enters the direct evaporative cooler 2 to have a direct heat and mass transfer with the circulating spray water. In this way, the temperature of the circulating water is lowered by the evaporative cooling principle of water, to achieve the cooling effect. At last, the hot humid air is finally discharged by the exhaust fan 3 to the outside. In the unit, water is carried by a circulating water pump through 2 paths. As one path, water enters into the chiller air cooler 1 to pre-cool the outdoor air. As the other path, water flows into the user side 5 and serves as a cold source to output the cooling capacity. Cooling of such chillers is achieved mainly through 3 processes. Chen Qun et al. gave a detailed theoretical description of the 3 processes [29], as follows.

1) Heat and mass transfer of the direct evaporative cooling section:

\[
m_w \cdot c_p \cdot w \cdot dT_w = k_a (T_a - T_w) \cdot dA
\]

\[
+k_a (d_w - d_a) \cdot dA
\]

\[
m_a \cdot c_p \cdot a \cdot dT_a = k_a (T_a - T_w) \cdot dA
\]

\[
\gamma_a m_a \cdot d \cdot d = \gamma_a k_a (d_wa - d_ag) \cdot dA
\]

2) Heat transfer of air cooler 1 and user heat exchanger 5:
\[ Q_1 = (k_s A) \frac{\left( t_w - t_{1,\text{out}} \right) - \left( t_{w,1} - t_{1,\text{in}} \right)}{\ln \left( t_w - t_{1,\text{out}} \right) - \ln \left( t_{w,1} - t_{1,\text{in}} \right)} \]

\[ Q_1 = m_{w,1} c_p, w \left( t_{1,\text{out}} - t_{1,\text{in}} \right) = m_{a,1} c_p, a \left( t_w - t_{w,1} \right) \]

\[ Q_5 = (k_s A) \frac{\left( t_n - t_{5,\text{out}} \right) - \left( t_n - t_{5,\text{in}} \right)}{\ln \left( t_n - t_{5,\text{out}} \right) - \ln \left( t_n - t_{5,\text{in}} \right)} \]

\[ Q_5 = m_{w,5} c_p, w \left( t_{5,\text{out}} - t_{5,\text{in}} \right) = m_{a,5} c_p, a \left( t_n - t_n \right) \]

3) Mixing of circulating water

\[ m_{w,1} + m_{w,5} = m_{w,2} \]

\[ m_{w,1} \cdot t_{1,\text{out}} + m_{w,5} \cdot t_{5,\text{out}} = m_{w,2} \cdot t_{w,\text{in}} \]

The above equations can be combined to solve the parameters of the state point in the circulation of the evaporative cooling chiller. As can be seen from Figure 10, to get the outlet water for the sub-wet bulb temperature, the indirect-direct evaporative cooling chiller of this mode should use a part of cold water produced by the chiller itself to pre-cool the outdoor air, so as to lower the air-in temperature into the direct evaporative cooler. So, the amount \( m_{w,1} \) of cold water flowing into the heat exchanger 1 affects the amount of terminal cold water \( m_{w,5} \). By comparing the heat conduction process and electric conduction process, Zeng Zengyuan, et al. of Tsinghua University defined a physical quantity “Huoji” (entranspy) for describing the heat transfer capacity. On the basis of research on the physical mechanism of evaporative cooling, Chen et al. proposed the notion of “wet air entranspy” for characterizing the heat absorption capacity of wet air. According to calculation results, in this working condition, when \( m_{w,1}/m_w=0.14 \), both the minimum entranspy dissipation resistance and maximum exergy efficiency correspond to the maximum total cooling capacity [30].

Xie Xiaoyun and other researchers from Tsinghua University made a test of this unit and found that in a project of Shihezi, Xinjiang, this unit had a water-out temperature of 18.55°C, which was 3.35 higher than the dew-point temperature and 1.5 °C lower than the wet-bulb temperature [30]. And their calculation results show that the sub-wet bulb efficiency of this indirect-direct evaporative cooling chiller was 115%.

As can be seen from Figure 11, 14% of the outlet water must be used to pre-cool the outdoor air, in order to get the cold water for achieving the sub-wet bulb temperature. That is to say, if we assume that the cold water amount for the sensible heat end is 25 m³/h, the direct evaporative cool should be designed to have about 29m³/h circulating water. Undoubtedly, this will increase the size and cost of the unit. Worse still, if the air cooler is used in areas with a poor air quality such as the northeast of...
China, passageways will be easily blocked, thus affecting the application effect of the air cooler. If its pre-cooler fails to perform its function of cooling air, the unit will fail to get the cold water for reaching a sub-wet bulb temperature.

As shown in Figure 11, in order to pre-cool the air in the evaporative cooling chiller packing section, besides the traditional air cooler, the tubular indirect evaporative cooler also has the effect of pre-cooling the outdoor air. Moreover, the tubular indirect evaporative cooler has larger pipe spacing, compared with other forms of heat exchangers. Applied in the northwest and other regions, this tubular indirect evaporative cooler can effectively prevent the blockage or fouling which is a common phenomenon when a cold cooler and a plate-fin type indirect evaporative cooler is used in the seriously windy and dusty northwest. Such equipment has a relatively higher pre-cooling efficiency, smaller flow resistance, greater convenience of maintenance and cheaper prices, so it has been widely used in evaporative cooling air-conditioning projects in recent years. In an evaporative cooling chiller, the tubular indirect evaporative cooler can be selected and used to fully exploit the advantages of evaporative cooling to improve the pre-cooling capacity of the unit and send all the high-temperature cold water produced by the unit to the end, instead of using the cold water produced by the unit itself to pre-cool the unit’s inlet air. Water pouring outside the pipe of the tubular indirect evaporative cooler is circulating water. This increases the cooling output capacity of the unit, and lowers the unit’s own resistance. All the high-temperature cold water that the unit produces for achieving the sub-wet bulb temperature is sent to the end to output the cooling capacity. To meet the same end cooling capacity requirement, the direct evaporative cooler configured by the unit is smaller than that of Figure 10, which effectively reduces the unit’s size. Figure 12 is an indirect-direct evaporative cooling chiller developed on the basis of the principle in Figure 11. This chiller is applied to an office building in Xinjiang.

![Figure 12. Picture of the indirect-direct evaporative cooling chiller.](image1)

![Figure 13. Test data of the unit.](image2)

Figure 13 lists the measured data of the unit. According to a test of the unit in practice, the author found that the unit’s water-out temperature ranges between 15.8 and 18.1 °C, which is always lower than the outdoor air wet bulb temperature (19.5-20.5 °C). According to calculation results, the unit’s sub-wet bulb efficiency is 120%. By comparison, it is found that the sub-wet bulb efficiency of this unit is slightly higher than that of the structure in Figure 11. In actual engineering, this unit can well satisfy the system requirements.

4. Conclusions
To explain the cold air/water below the wet bulb temperature produced by using the evaporative cooling technology, this paper proposes the notion of sub-wet bulb temperature and sub-wet bulb...
efficiency is proposed, to briefly characterize the air-in/air-out temperature and water-out temperature of the indirect-direct evaporative cooling air handling unit and chiller. The outlet air temperature and the outlet water temperature. The sub-wet bulb efficiency is used to characterize the efficiency of the indirect-direct evaporative cooling equipment, to visually indicate the relationship between the outdoor air wet bulb temperature and the sub-wet bulb temperature and reveal the degree to which the sub-wet bulb temperature goes beyond the outdoor air wet bulb temperature. Moreover, this paper also introduces the measures of air-cooling evaporative equipment and water-cooling evaporative cooling equipment to achieve a sub-wet bulb temperature. According to the test data, the sub-wet bulb efficiency of the indirect-direct evaporative cooling equipment in Iran is 106%, while the sub-wet bulb efficiency of the indirect-direct evaporative cooling air handling unit produced in China is 117%. For the indirect-direct evaporative chiller, foreign scholars have given the idea of producing the cold water for achieving the sub-wet bulb temperature, but have not obtained the actual test data. According to an analysis on the test data of the author and other scholars, the sub-wet bulb efficiency of surface pre-cooling evaporative chillers is 115%, and the sub-wet bulb efficiency of tubular pre-cooling evaporative chillers is 120%.

On the basis of analyzing the use of the sub-wet bulb temperature to characterize the degree to which the temperature of water/air handled by different evaporative cooling equipment goes close to the wet bulb temperature, this paper argues that the sub-wet bulb temperature can be used to the temperature that the indirect-direct evaporative cooling equipment can reach by handling water/air, and the sub-wet bulb efficiency can be used to characterize the degree to which such equipment can go below the wet-bulb temperature.

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