A Review of Models on Direct Evaporative Cooling

*Michael Wilkins & Nelson Fumo**

Department of Mechanical Engineering, University of Texas at Tyler, Tyler, TX

https://doi.org/10.33697/ajur.2023.086

Students: mwilkins5@patriots.uttyler.edu, mtwilkins903@gmail.com
*Mentor: nfumo@uttyler.edu**

ABSTRACT
Direct evaporative cooling (DEC) is a technology that is continuously expanding into different areas of study. The foundation of this process has been built through expansive research efforts and physical experimental data. The ability to accurately model and predict the performance of DEC systems allows the energy-efficient process to gain traction in HVAC applications, however, the inconsistencies present among research efforts created discontinuities in the reproduction of a system. By reviewing current literature, the discrepancies in the defining methodologies of how DEC systems are defined and predicted can provide insight to future research. This review depicts the different approaches taken in recent research to define the equations that govern the thermodynamic processes, the different materials used in the process, and the models used to predict the performance of DEC systems. By identifying the most common practices in current research, the gaps in literature can be recognized and overcome in further efforts.

KEYWORDS
Direct Evaporative Cooling; Evaporative Cooler; Evaporative Cooling Media; HVAC; Cooling Effectiveness

INTRODUCTION
The ever-growing issue of increasing global energy consumption and CO_2 emissions[1] demands a further review of pertinent solutions. Throughout the years, since its invention, air conditioning systems have become an integral part of most commercial buildings and households, which are responsible for a considerable amount of the total energy consumed worldwide. The U.S Department of Energy states that roughly 6% of all supplied energy is consumed by household air conditioners, with even larger numbers corresponding to commercial building HVAC systems[2]. The necessity to improve efficiency and decrease power consumption related to HVAC systems is crucial to the sustainability of the future. Evaporative cooling (EC) has the potential to help HVAC systems achieve these objectives.

EC is a fairly simple process that is capable of producing economical cooling when weather conditions are appropriate, an aspect of which is part of the limitations preventing the larger market penetration of evaporative cooling technology. While evaporative coolers are known to achieve significant temperature drops in more arid climates, they are also known they can provide relief from the heat in any climate with high temperatures. The evaluation of similar EC processes has yet to gain uniformity among available research, which causes discontinuities in the progression of the technology over time. To further research efforts and optimize this process for expanded use in the HVAC industry, there must be common methods of practice for defining EC systems and their associated performance parameters. In doing so, the uncertainty involved in research can be addressed and overcome, leading to a faster progression of the advancement of evaporative cooling technologies. The appropriate design and optimization of EC systems relies on the ability of accurate models to reproduce how the system will perform. This study focuses on models for the evaporative cooling process that occurs at the media of an EC system. As shown in **Figure 1**, the first component of a basic DEC system is a media that allows for an increase in the contact, and therefore heat and mass transfer, between the air to be conditioned and the water used to condition it. Another component includes a water recirculation subsystem in which a pump takes water from a water sump and supplies it to the water distributor that will uniformly distribute the water over the media. The last component is a fan that moves the air through the media.

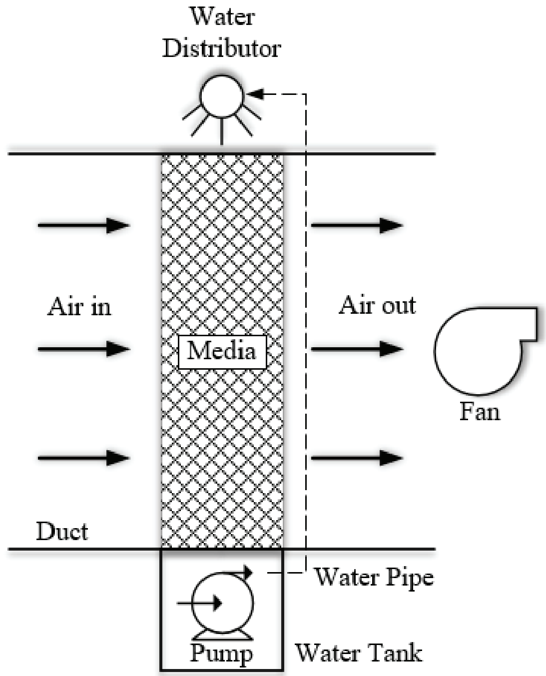

Figure 1. Basic layout of a DEC cooler.

Every component of the EC system has an impact on the overall performance of the EC system, whose objective is to lower the temperature of incoming air by increasing its moisture content in an adiabatic process in which the air is cooled at constant wet-bult temperature. This is achieved by transferring heat from the air to the water, which causes an evaporation effect as the air flows through the water-saturated media[3]. The water contained in the sump is delivered to the system with the intention of fully saturating the media; however, full saturation is influenced by each component. The media's ability to saturate completely is referred to as "saturation efficiency". This concept and the associated issues are discussed in further detail in *Water Distribution Methods*. Since the incoming air stream will be cooled at a constant wet-bulb temperature, the maximum attainable temperature drop is determined by the initial dry bulb temperature and the humidity of the incoming air as seen in **Figure 2**. The process moves the state of the air from "inlet" to "outlet" along the wet-bulb line, which creates the assumption that no other methods of heat transfer are affecting the airflow.

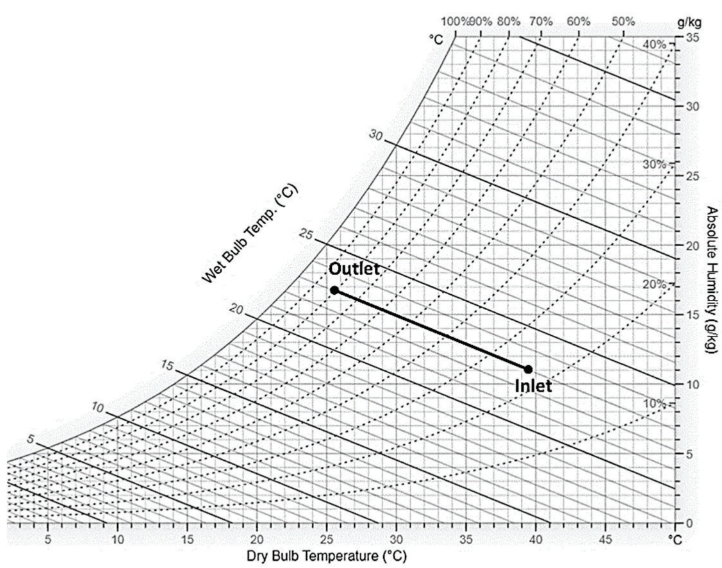

Figure 2. Psychometric process of DEC.

The methods of evaluating and predicting the performance of EC systems often exclude the layout of the EC system being analyzed. The inclusion of stating the physical layout of the analyzed systems is imperative to fully define the characteristics of each system. Furthermore, the equations to determine the efficiency of these systems vary among previous research efforts. This creates inconsistencies in the continual improvement of the involvement of EC systems in various applications.

The performance evaluation of EC systems is determined by design parameters affecting the thermodynamic process. How the evaluation process is described depends on the type of approach or model used, which is reviewed and presented in this paper. There are many ways to characterize EC systems based on the components and conditions that make up the systems, however there are limited resources that help to distinguish how these characteristics perform given the application. The ability to model the operating conditions of each component of an EC system would provide insight into the design of the components and layout of these systems. This review serves the purpose of providing a comparison of systems and applications with focus on the models for media performance, as a means of defining characteristics of current research efforts on DEC systems.

THERMODYNAMIC ANALYSIS OF DEC SYSTEMS

The performance of a DEC system is determined by the ability to modify the thermodynamic properties of the air as it exits the system. The measure of efficiency may be approached in different ways, therefore uniformity among presented results should be considered based on the method of analysis of the system. In **Table 1**, the various equations used to determine the efficiency are represented, along with the researchers that support the equation.

	Property	Equation	Reference
COOLING EFFICIENCY	Temperature	$\varepsilon = \frac{T_{inlet}-T_{outlet}}{T_{inlet}-T_{wb}}$ (1)	**4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17**
	Humidity Ratio	$\varepsilon = \frac{\Delta\omega}{\Delta\omega_{maximum}} = \frac{\omega_{inlet}-\omega_{outlet}}{\omega_{inlet}-\omega_{maximum}}$ (2)	**18, 19**
	Enthalpy	$\varepsilon = \frac{h_{outlet}-h_{inlet}}{h_{wb,outlet}-h_{inlet}}$ (3)	**20**
	Exergy	$\varepsilon = \frac{h_{inlet}-h_{outlet}-T_{inlet}(s_{inlet}-s_{outlet})}{h_{inlet}-h_{wb,inlet}-T_{inlet}(s_{inlet}-s_{wb,i})}$ (4)	**1**

Table 1. Efficiency equations and references.

As seen from **Table 1**, the most common method of determining the efficiency of a DEC is based on temperature. For this case, the performance is better called effectiveness as it compares the inlet and outlet air dry-bulb temperatures with the maximum possible change in air dry-bulb temperature, which is also called wet-bulb depression. This approach only considers the effects on the airflow and does not state the quality of the supplied water to the system. As a result of this, for a specific airflow rate and air inlet condition, the DEC system may perform inconsistently based on the inlet temperature of the water being supplied to the system. The humidity ratio approach is less common throughout research. This may be due to methods of measuring humidity, as well as its associated accuracy, in comparison to the simplicity of temperature measurements. The psychometric performance evaluation of the system using the enthalpy approach considers temperature and humidity of the airflow for a more extensive approach in determining the efficiency of the DEC system. The exergy approach, stated in the review by S. R. Pinar Mert Cuce et al[1], follows the same ideology as the enthalpy approach, but adds an exergy destruction term. Exergy destruction is directly related to the second law of thermodynamics and describes the system's irreversible losses. This provides an added element of reliability to the statement of the system's operation and efficiency.

Coefficient of Performance

The coefficient of performance of a DEC thermodynamic process relates to the amount of cooling from the evaporative cooling effect and the power used by the system, which is associated to the fan and water pump. For EC systems, the input energy to system typically is associated to the pump work and the fan work; however, the standard form of the equation applies to all the research included in this review, as seen in **Equation 1**.

$$COP = \frac{Q_{c,e}}{\Sigma W}$$ **Equation 1.**

For the COP equation, $Q_{c,e}$ represents the effective heat exchange performed by the system and ΣW is the summation of all the work inputs to the system. As can be noticed, the *COP* is a measure of the system performance and the effectiveness is a measure of the efficiency of the psychrometric process, which defines the cooling capacity. As expected, there was no difference in how the *COP* was determined among authors.

Input Parameters

To determine a DEC system's performance, the measured and controlled variables that describe the inlet conditions of the system must be defined. The various subsystems of a DEC system can be divided into three main areas: airflow, water distribution, and EC media. To accurately define the state of the airflow entering and exiting a DEC system, the psychometric properties and the flow rate must be stated. As seen in **Table 2**, the defining factors used in research can be separated by the airflow's input variables.

	Parameters	Symbols	Reference
INPUT PARAMETERS	Temperature, Humidity Ratio and Velocity	$T_{inlet}, \omega, v_{inlet}$	**4, 5, 13, 14, 17, 18, 22**
	Temperature, Humidity Ratio, and Volumetric Flow Rate	$T_{inlet}, \omega, \dot{V}_{inlet}$	**8, 15**
	Temperature, Velocity, and Molar Concentration	$T_{inlet}, v_{inlet}, c_{a,in}$	**9, 11**
	Temperature, Humidity Ratio, and Mass Flow Rate	$T_{inlet}, \omega, \dot{m}_a$	**10, 12**
	Temperature, Humidity Ratio, Pressure, and Specific Enthalpy	$T_{inlet}, \omega, P, h_a$	**20**

Table 2. Input parameters of DEC systems.

Water Distribution

The water distribution subsystem consists of many different components that impact the performance of a DEC system. This includes the supply water, the pump, and the method of distributing the water. The defining qualities of the water as part of a DEC system are the temperature and the mass flow rate. Although well know, the associated formula for pump work is given to illustrate its consistent use among researchers and is shown in **Equation 2**.

$$W = \frac{Q_w \rho_w H_p g}{\eta_{pump}}$$ **Equation 2.**

In **Equation 2**, Q_w represents the volumetric flow rate of the water, ρ_w describes the water's density, H_p is the total head, η_{pump} is the total efficiency of the pump, and g is gravity.

EC Media Input Characteristics

The performance of the media used in DEC systems is also described by many different parameters which, as stated before, creates a divide in how the DEC media is classified among researchers. **Table 3** shows the various terminology and data used to describe a material's effectiveness.

	Terminology	Reference
EFFECTIVENESS	Saturation Efficiency	**22**
	Unity Wettability Factor	**6**
	Cooling Capacity	**8**
	Heat Transfer Coefficient	**9**
	Mass Transfer Coefficient	**9**
	Water Absorption Capacity	**10**

Table 3. Effectiveness of DEC media.

It should be stated that the differences in terminology of the effectiveness of EC media primarily stems from the goal of the research. However, the various methods of describing the performance lack consistency and uniformity in the research reviewed.

EVAPORATIVE COOLING MEDIA

The main component of the DEC system is the media that defines the area of heat and mass transfer for the air flowing through the media, resulting in a reduction in air temperature in conjunction with an increase in humidity. The evaporative media can be broken down into certain controlled characteristics that impact a DEC system's efficiency:

1. Material
2. Cross Sectional Area
3. Thickness
4. Shape

Each of these characteristics play a role in how the media performs based on the given application. Manipulation of these characteristics can result in an increase in efficiency; however, the system may be penalized by an increase in undesirable qualities such as pressure drop. The optimal arrangement of these variables can allow the system to achieve its purpose with minimal negative qualities.

The DEC pad's material and shape affect performance parameters such as saturation capacity and pressure drop. Losses in efficiency are introduced in many ways, such as when the material is unable to saturate completely and requires a greater flow rate to keep the contact surfaces moist. The shape and size of the material also introduces losses to the system by increasing the pressure drop. Pressure drop decreases the overall efficiency of the system by requiring more power to achieve the desired rate of airflow through the system. Of the four characteristics of DEC pads, the material has a great influence on the others due to material constraints and manufacturing abilities. The materials found to be used in the literature reviewed for this study are further analyzed and compared in the following section.

Material:
Evaporative cooling pads can be broken down into the three main categories: rigid pads, fiber pads, and package/fill pads[3]. The primary reason for experimentation with different materials or types of pads is to attempt to find materials with greater saturation capacity, which correlates to heat and mass transfer to the airflow across the media.

Rigid Pads:
Rigid pads most commonly consist of a series of individual sections of material, which are formed to a specific shape to optimize surface area and assembled with an adhesive of joining process that affect the materials pressure drop and air flow characteristics. **Figure 3** shows the relative geometric properties of this type of pad.

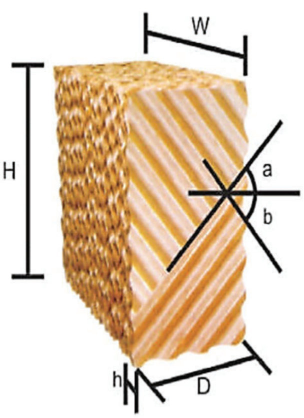

Figure 3. Geometric properties of rigid pads[21]

A major benefit of rigid pads is the inherent ability to design shape profiles for a specific application. As the most used rigid media currently being researched, CELdek has numerous studies on sizing systems based on airflow requirements. **Figure 4** represents the performance of this type of rigid pad comparing different thicknesses, over a wide range of flowrates.

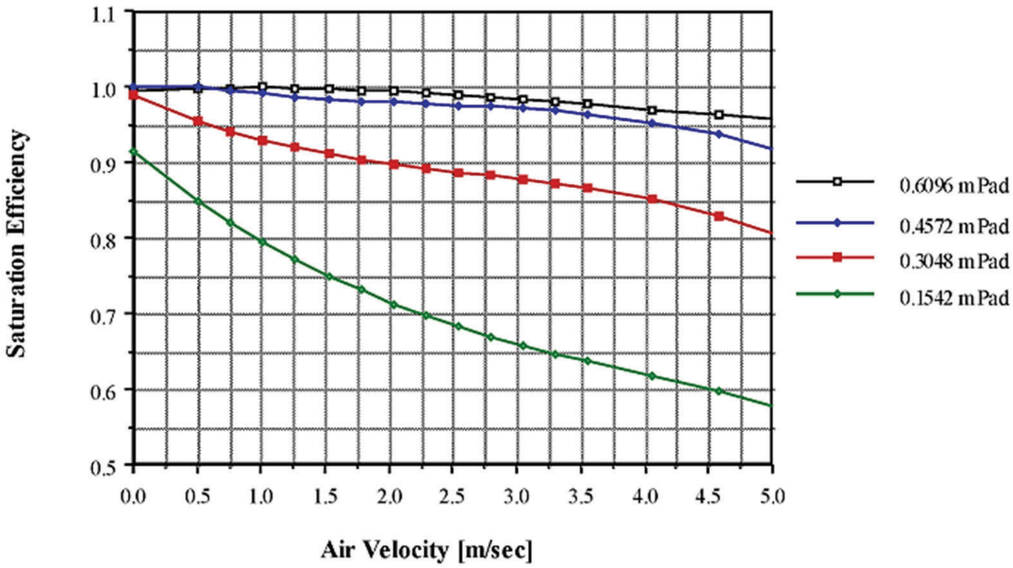

Figure 4. Saturation efficiency vs. pad thickness of Celdek DEC pads[23]

Figure 4 follows the curve fit equation represented in **Equation 3**[23], with input variables being the thickness, depth of the pad, and the incoming air velocity.

$$\varepsilon = 0.792714 + 0.958569t - 0.25193\mathrm{v} - 1.03215t^2 + 0.0262659v^2 + 0.914869(t * v) - 1.48241(v * t^2) - 0.018992(v^3 * \mathrm{t}) + 1.13137(t^3 * v) + 0.0327622\,(v^3 * t^2) - 0.145384(v^2 * t^3) \quad \textbf{Equation 3.}$$

Fiber Pads

Fiber pads primarily consist of organic or synthetic materials that are woven together and joined using an adhesive or a joining process. These pads have attributes that can be controlled through the manufacturing process, such as thickness, cross-sectional area and spacing of the fibers. This allows the designer to control characteristics such as the pad's potential for saturation capacity, pressure drop and airflow capacity. Common materials used in fiber pads include vegetable fibers, textile fibers or woven fabrics, paper, wood, plastic, or stone[3]. A common fiber pad used in the industry is produced by AirCare and is shown in **Figure 5**.

Figure 5. Fiber pad produced by AirCare[31].

It should be noted that only one of the researchers included in this review generated a predictive model using this material as a DEC media[17].

Package/Fill Pads

Package pads, otherwise known as fill pads, use less structured materials contained within a case to distribute the flow through the media. The media used to fill the case usually consists of porous and inorganic materials, such as volcanic stones or expanded clay. The casing material is constructed with plastic or metal mesh. This limits the restrictive qualities contained with most media pads and allows flow through the structure depending on the type of media contained within the casing[3]. This type of pad lacks manufactured options within the market and no researchers in this review provided predictive modeling using this specific type of DEC media pad.

DIRECT EVAPORATIVE COOLING PAD MODELS

The implications of DEC systems are expanding as research continues and advancements in manufacturing capabilities increase. The type of EC model used in each application has the potential to alter the determination on if the DEC system is a viable enhancement or a detriment. The use of desiccant systems may be beneficial for systems utilizing rigid media pads, however, may not have a significant effect on other types of media pads. Through a review of the many different applications of DEC systems in current research, the progress of DEC in the future of HVAC and efficient heat exchange systems may be optimized.

As a starting point to discuss the models for analyzing DEC, the authors want to clarify that, when possible, the models were classified as data-driven, engineering, or hybrid models. The data-driven models are those that use any type of statistical approach such as regression analysis, artificial intelligence such as neural networks, or support vector machines among others. The engineering models use physical principles describing the natural phenomena affecting system behavior. The hybrid or grey models are a combination of the previous two, which are developed when the physical information of the system does not allow defining the system completely and the parameters needed for a full description of the system are obtained by statistical analysis. As for any model that is not developed from a pure analytical analysis, experimental data is needed for validation. In this sense, it is important to consider the **ANSI/ASHRAE Standard 133-2015** Method of Testing Direct Evaporative Air Coolers[24] as a reference when performing experiments. This is particularly important regarding accuracy for air parameters such as temperatures, air flow, water flow, and pressure drop.

Data Driven Models:

Data driven models are those formulated based strictly on experimental data obtained from physical testing. These models are often dependent on the characteristics of the physical setup associated with the experiment, therefore should be carefully considered when conducting further research.

The Engineering Reference[25] of the whole building energy simulation program **EnergyPlus** [26] uses a multi-variate least squares curve fit to estimate the saturation efficiency (ε)as a function pad face velocity (*Airvel*) and pad thickness (*Depth*). The coefficients of the third order quadratic curve fit shown in **Equation 4** [25] were obtained using data from the manufacturer of the CelDek rigid media pad.

$$\begin{aligned}\varepsilon = 0.792714 &+ 0.958569(Depth) - 0.25193(Airvel) - 1.03215(Depth^2) + 0.0262659(Airvel^2)\\ &+ 0.914869(Depth \times Airvel) - 1.48241(Airvel \times Depth^2)\\ &- 0.018992(Airvel^3 \times Depth) + 1.13137(Depth^3 \times Airvel)\\ &+ 0.0327622(Airvel^3 \times Depth^2) - 0.145384(Depth^3 \times Airvel^2)\end{aligned}$$

Equation 4.

In the experimental process performed by M.C. Ndukwu et al.[17], a modeling equation was used which was based on physical data for the different materials used in the experiment. The variables included in the model were inlet air temperature, wet bulb temperature, relative humidity, mass flow rate of the air, and volume of the humidifier as shown in **Equations 5-7**. The output of the equation is the outlet air temperature of the DEC system.

Jute Fiber: $R^2 = 0.81$

$$T_c = T_{ab} - [(T_{ab} - T_w)(0.226 - 0.0094\omega + 2.55\dot{m}_a + 0.00203V_H)]$$

Equation 5.

Palm Fruit Mesocarp Fiber: $R^2 = 0.78$

$$T_c = T_{ab} - [(T_{ab} - T_w)(0.182 + 0.0131\omega - 0.0546\dot{m}_a + 0.0016355V_H)]$$ **Equation 6.**

Wood Charcoal: $R^2 = 0.76$

$$T_c = T_{ab} - [(T_{ab} - T_w)(1.52 - 0.006288\omega - 1.739\dot{m}_a - 0.00912V_H)]$$ **Equation 7.**

In a physical experiment performed by S.A. Nada et al.[20], heat and mass transfer characteristics of corrugated cellulose papers were evaluated and modeled using data obtained from an experimental setup at Benha University (Egypt). Regressions were formulated and documented with the associated error ranges associated. The formulas use the inlet air temperature, water temperature, mass flow rate of the water, the evaporative pad thickness(δ), Reynold's number, and Prandtl's number. The equations for the outlet air temperature and the relative humidity are shown in **Equations 8-9**.

$$t_{a,out}(°C) = 21.2\left(\frac{t_{a,in}}{t_{a,Ref}}\right)^{0.752}\left(\frac{t_w}{t_{w,Ref}}\right)^{1.275}\left(\frac{\dot{m}_w}{\dot{m}_{w,Ref}}\right)^{-0.0313}\left(\frac{\delta}{\delta_{Ref}}\right)^{-0.099} Re^{0.133}Pr^{0.33}$$ **Equation 8.**

$$RH_{out}(\%) = 200.1\left(\frac{t_{a,in}}{t_{a,Ref}}\right)^{0.298}\left(\frac{t_w}{t_{w,Ref}}\right)^{0.405}\left(\frac{\dot{m}_w}{\dot{m}_{w,Ref}}\right)^{0.145}\left(\frac{\delta}{\delta_{Ref}}\right)^{0.16} Re^{-0.088}Pr^{0.33}$$ **Equation 9.**

Engineering Models

Throughout the research, the vast majority of engineering models were all validated by previously performed physical experimentation. There was a lack of predictive modeling based on mathematical concepts alone.

Hybrid Models

In the research regarding parameters affecting direct and indirect evaporative cooling systems[27], the authors state that the data corresponds to experiments conducted at BZU Multan (Pakistan) and references for the detailed information are given.

The surrogate model proposed by Hussain et al.[27] uses meteorological data (dry bulb temperature, dew point temperature, wet bulb temperature, relative humidity, enthalpy, and humidity ratio) and system parameters (area and inlet velocity) as inputs to a Gaussian process that feeds a neural network to predict system performance.

Research performed by Qi Zhang et al.[11] describes a numerical model that is a tested and validated expansion of the physical experimentation tested by Yan et al.[28]. The authors use computational geometry based on the EC media "CELdek 7060", which is implemented with associated equations into a finite element software. The simulation follows logarithmic distribution laws for the temperature layers of grid node layouts. A SIMPLE algorithm is used for the analysis and the turbulent model is consistent with a turbulent kinetic energy(ϰ) and dissipation rate(ε) for the control volume and adjacent areas. It was reported that a 0.32℃ error differential was calculated between the physical and numerical models.

A performance analysis was performed by Xin Cui et al.[9] as a numerical validation of previous research performed by Xiangjie Chen et al.[29]. The membrane-based DEC system was modeled in the COMSOL Multiphysics environment and solved by using three physical models: the heat transfer mode, the laminar flow mode, and the transport of diluted species mode. The temperature, concentration, and the velocity fields of the domain were solved simultaneously in the simulation.

Research on the application of hollow fiber membranes in EC systems was performed and modeled by Weichao Yan et al.[32]. As a nontraditional form of evaporative cooling, the typical dimensions of the evaporative cooling media are replaced with descriptive dimensions of the membrane being used in the experimental process. This creates additional input parameters to the predictive modeling shown in outlet temperature and relative humidity **Equations 10 - 11**. The equations also have associated parameters outlining the constraints of each element within the applicable range of modeling within the research paper. The parameters in **Equations 10 - 11** are temperature (*T*), relative humidity (*RH*), velocity (v), length (*L*), diameter (*d*), thickness (δ), packing fraction (φ), and water – air ratio (μ).

$$T_{out} = -0.6204 + 0.612T_{in} + 7.049\omega_{in} + 1.922\upsilon - 1.660\mu - 13.094L + 10.830d_i + 12.888\delta - 51.065\varphi + (0.476T_{in}\omega_{in}) + (0.024T_{in}\upsilon) - (0.787T_{in}\varphi) - (2.012\omega_{in}\upsilon) + (13.787\omega_{in}L) - (6.903\omega_{in}d_i) + (71.092\omega_{in}\psi) - (0.769\upsilon\mu) - (3.926\upsilon L) + (2.135\upsilon d_i) + (8.263\upsilon\delta) - (16.638\upsilon\varphi) - (12.490Ld_i) - (50.080L\delta) + (83.675L\varphi) - (55.262d_i\varphi) - (5.246{\omega_{in}}^2) + (3.255\mu^2) + (22.738L^2) + (348.796\varphi^2)(°C)$$

Equation 10.

$$RH_{out} = 0.415 + 0.008T_{in} + 1.518\omega_{in} - 0.2329\upsilon - 0.027\mu + 0.316L - 0.404d_i - 5.147\delta + 4.439\varphi + (0.062T_{in} * \delta) - (0.201\omega_{in} * \upsilon) - (1.155\omega_{in} * L) + (0.188\omega_{in} * d_i) + (3.983\omega_{in}\delta) - (4.285\omega_{in}\varphi) + (0.123\upsilon L) - (0.077\upsilon d_i) + (0.601\upsilon\varphi) + (0.372Ld_i) - (2.038L\varphi) + (2.004d_i\varphi) - \left(0.0001{T_{in}}^2\right) - (1.272{\omega_{in}}^2) + (0.013\upsilon^2) - (1.276L^2) - (16.070\varphi^2)$$

Equation 11.

Research performed by M. Lata et al.[30] outlines a finite difference method utilizing MATLAB. The heat and mass transfer approach implements energy balance equations for the system. The system variables used in the simulation are mass flow of air, mass flow of water, thickness and surface of cooling pad, and the inlet temperature conditions of both the air and water. The mathematical model was validated using experimental data obtained by the authors in 2018 in Ahmedabad, Gujarat, India.

Physical Model Experimental Structure

The literature reviewed in this research is displayed in **Table 4** by analyzing the application, in conjunction with the type of DEC pad material, water delivery system, and the size of the media pad.

The idea of this section is to refer and briefly describe the different types/arrangements found as source of models. For example, from the first set of papers:

MODEL	EVAPORATIVE MEDIA	WATER DELIVERY	MEDIA SIZE
Ground source direct evaporative cooling[5]	Not Stated	Pulverized nozzles	Not Stated
Evaporative cooling with pre-dehumidification with activated carbon fiber[4]	GLASdek7090	Spray nozzles	500 mm × 400 mm × 300 mm
Evaporative cooling with post-dehumidification Aluminophosphate zeolite[18]	Cellulose coated with AlPo zeolite desiccant	Spray nozzle	200 mm x 200 mm x 198 mm
Regenerative Evaporative cooling[6]	Kraft Paper	Not stated	1200mm x 80mm x 5 mm gap thickness
Various Cross-Sectional Metal Sheet Shapes[22]	Aluminum	Perforated distribution tube/pipe	700mm x 700mm x 200mm
Desiccant assisted cooling systems[10]	Wood Chips, Yellow Stone, Pumice, Eucalyptus Fibers, Vermiculite	Spray Nozzle	240mm Diameter x 50mm
Peformance Enhancement of DE builidng[20]	Corrugated Cellulose Fibers, "beehive" structure	Steel pipe with evenly spaced holes	335mm x 390mm x (35,70,105,140) mm
Numerical Simulation[11]	CELdek7060	Distribution Pipe	300mm x 200mm x 28mm

Table 4. Models of DEC systems.

DISCUSSION & CONCLUSION

The purpose of this research was to review the performance models of DEC systems. The review of this material allows for the methodology of each researcher to be compared based on similarities and differences. The defining characteristics of the DEC systems, the setups and types of media, and methodology of model generation all impact the cohesiveness of research efforts. As discussed, the equations defining cooling efficiency as well as the input parameters used in various literature lack consistency, which limits the amount of comparable data for the different processes. The approach taken by researchers, as stated in the literature, was to describe processes in a manner that was deemed suitable per given application, which resulted in widespread variance. The "hybrid" direct evaporative cooling pad models outnumbered the amount of solely data driven models and engineering models. This states that the majority of researchers use experimental data to either validate the performance models or aid in the derivation of a mathematical model. Throughout the reviewed literature, there are numerous researchers testing various DEC topologies and media, however none of them provided modeling for performance based on the described parameters. This study shows the need of the search of general accepted method for development of models for DEC systems, which prevalence is toward hybrid models.

ACKNOWLEDGEMENTS
The authors express gratitude for the support received from the ASHRAE East Texas Chapter in the form of a scholarship.

Nomenclature

COP	*Coefficient of Performance*
DEC	*Direct Evaporative Cooling*
EC	*Evaporative Cooler*
T	*Temperature (°C)*
P	*Pressure*
RH	*Relative Humidity*
C_{pa}	*Specific Heat of Air*
$\dot{m}$	*Mass Flow Rate*
ε	*Effectiveness*
ϱ	*Density*
h	*Enthalpy*
$\dot{W}_p$	*Pump Work*
$\dot{W}_f$	*Fan Work*
wb	*Wet bulb*

REFERENCES

1. S. R. Pinar Mert Cuce. (2016) A state of the art review of evaporative cooling systems for building applications, *Renewable and Sustainable Energy Reviews* 54, 1240-1249. *https://doi.org/10.1016/j.rser.2015.10.066*
2. U.S. Department of Energy, *Air Conditioning*, *https://www.energy.gov/energysaver/air-conditioning* (accessed Nov 2022)
3. A. Tejero-González, A. Franco-Salas. (2021) Optimal operation of evaporative cooling pads: A review, *Renewable and Sustainable Energy Reviews* 151, no. 111632. *https://doi.org/10.1016/j.rser.2021.111632*
4. Bianfeng Yang, Cong Wang, Xu Ji, Ren Zhang, Xirong Yue, Junneng Nie. (2022) Two-stage evaporative cooling system with composite activated carbon fiber dehumidification, *International Journal of Thermal Sciences* 179, no. 107725.
5. Gokhan Yıldız, Alper Ergün, Ali Etem Gürel, Ümit Agbulut, Servet Eser, Asif Afzal, C.Ahamed Saleel. (2022) Exergy, sustainability and performance analysis of ground source direct evaporative cooling system, *Case Studies in Thermal Engineering* 31, no. 101810. *https://doi.org/10.1016/j.csite.2022.101810*
6. Sarvesh Kashyap, Jahar Sarkar, Amitesh Kumar. (2022) Comparative performance analysis of different novel regenerative evaporative cooling device topologies, *Applied Thermal Engineering* 176, no. 115474.
7. Manju Lata, Dileep Kumar Gupta. (2020) Experimental Investigation and Simulation of Modified Evaporative Cooling System, *Advances in Mechanical Engineering*, 441-448. *https://doi.org/10.1007/978-981-15-3639-7_52*
8. Weichao Yan, Xiangzhao Meng, Xin Cui, Yilin Liu, Qian Chen, Liwen Jin. (2022) Evaporative cooling performance prediction and multi-objective optimization for hollow fiber membrane module using response surface methodology, *Applied Energy* 325, no. 119855. *https://doi.org/10.1016/j.apenergy.2022.119855*
9. Xiangjie Chen, Yuehong Su, Devrim Aydin, Xingxing Zhang, Yate Ding, David Reay, Richard Law, Saffa Riffat. (2020) Performance analysis of a hollow fiber membrane-based heat and mass exchanger for evaporative cooling, *Applied Energy* 271, no. 115238. *https://doi.org/10.1016/j.apenergy.2020.115238*
10. Nima Khosravi, Devrim Aydin, Majid Karim Nejhad, Pervin Abohorlu Dogramaci. (2020) Comparative performance analysis of direct and desiccant assisted evaporative cooling systems using novel candidate materials, *Energy Conversion and Management* 221, no. 113167. *https://doi.org/10.1016/j.enconman.2020.113167*
11. Qi Zhang, Suoying He, Jun Cheng, Bin Zhao, Xuehong Wu, Mingxuan Yan, Ming Gao, Zhe Geng, Shuzhen Zhang. (2022) Numerical simulation of evaporative cooling process in a medium-gap-medium arrangement, *International Journal of Thermal Sciences* 179, no. 107700. *https://doi.org/10.1016/j.ijthermalsci.2022.107700*
12. Rekabra Youssef, Md Sazzad Hosen, Jiacheng He, Joris Jaguemont, Lysander De Sutter, Joeri Van Mierlo, Maitane Berecibar. (2021) Effect analysis on performance enhancement of a novel and environmental evaporative cooling system for lithium-ion battery applications, *Journal of Energy Storage* 37, no. 102475. *https://doi.org/10.1016/j.est.2021.102475*
13. Ali Hammoodi Mahdi, Issam M. Ali Aljubury (2021) Experimental investigation of two-stage evaporative cooler powered by photovoltaic panels using underground water, *Journal of Building Engineering* 44. *https://doi.org/10.1016/j.jobe.2021.102679*
14. Shiva Kumar, Sampath Suranjan Salins, S.V. Kota Reddy, Prasanth Sreekumar Nair (2021) Comparative performance analysis of a static & dynamic evaporative cooling pads for varied climatic conditions, *Energy* 223, no. 101136. *https://doi.org/10.1016/j.energy.2021.121136*
15. Ibrahim Atmaca, Ali Senol, Ahmet Çaglar. (2022) Performance testing and optimization of a split-type air conditioner with evaporatively-cooled condenser, *Engineering Science and Technology* 32, no. 101064. *https://doi.org/10.1016/j.jestch.2021.09.010*
16. Sujatha Abaranji, Karthik Panchabikesan, Velraj Ramalingam. (2021) Experimental study on the direct evaporative air-cooling system with vermicompost material as the water storage medium, *Sustainable Cities and Society* 71, no. 102991. *https://doi.org/10.1016/j.scs.2021.102991*
17. M.C.Ndukwu, M.I.Ibeh, E.C.Ugwu, D.O.Igbojionu, A.A.Ahiakwo, Hongwei Wu. (2022) Evaluating coefficient of performance and rate of moisture loss of some biomass humidifiers materials with a developed simple direct stand-alone evaporative cooling system for farmers, *Energy Nexus* 8, no. 100146. *https://doi.org/10.1016/j.nexus.2022.100146*

18. Seng Sunhor, Dendi Adi Saputra, Yugo Osaka, Takuya Tsujiguchi, Akio Kodama. (2022) Dehumidification behavior of an aluminophosphate zeolite coated crossflow heat exchanger driven with direct hot water heating and evaporative cooling, *Applied Thermal Engineering* 210, no. 118355. *https://doi.org/10.1016/j.applthermaleng.2022.118355*

19. Yuanyuan Zhou, Zhen Yan, Qiumin Dai, Yanshun Yu. (2021) Experimental and numerical evaluation of a two-stage indirect/thermoelectric assisted direct evaporative cooling system, *Energy Conversion and Management* 248, no. 114790. *https://doi.org/10.1016/j.enconman.2021.114780*

20. S.A. Nada, H.F. Elattar, M.A. Mahmoud, A. Fouda. (2020) Performance enhancement and heat and mass transfer characteristics of direct evaporative building free cooling using corrugated cellulose papers, *Energy* 211, no. 118678. *https://doi.org/10.1016/j.energy.2020.118678*

21. Ibrahim Dincer, Azzam Abu-Rayash. (2020) Chapter 6 - Sustainability Modeling, *in Energy Sustainability*, Academic Press, pp. 119-164.

22. Aleksejs Prozuments, Arturs Brahmanis, Armands Mucenieks, Vladislavs Jacnevs, Deniss Zajecs. (2022) Preliminary Study of Various Cross-Sectional Metal Sheet Shapes in Adiabatic Evaporative Cooling Pads, *Energies* 15, no. 11. *https://doi.org/10.3390/en15113875*

23. U.S. Department of Energy, *Evaporative Cooler Sizing*, in EnergyPlus™ Version 22.1.0 Documentation, pp. 584-585. (Accessed Nov 2022)

24. ASHRAE, ANSI/ASHRAE Standard 133-2015 *Method of Testing Direct Evaporative Air Coolers*, Atlanta, GA: ASHRAE, 2015.

25. Department of Energy, *Engineering Reference - EnergyPlus*™ *Version 22.1.0 Documentation*, 29 March 2022. [Online]. *https://energyplus.net/documentation*. [Accessed Dec 2022].

26. Department of Energy, *EnergyPlus*, 2022. *https://energyplus.net/*. [Accessed on December 2022].

27. Imtiyaz Hussain, Farzana Bibi, Showkat Ahmad Bhat, Uzair Sajjad, Muhammad Sultan, Hafiz Muhammad Ali, Muhammad Waheed Azam, Sachin Kumar Kaushal, Sajid Hussain, Wei-Mon Yan. (2022) Evaluating the parameters affecting the direct and indirect evaporative cooling systems, *Engineering Analysis with Boundary Elements* 145, 211-223. *https://doi.org/10.1016/j.enganabound.2022.09.016*

28. Mingxuan Yan, Suoying He, Na Li, Xiang Huang, Ming Gao, Mengfei Xu, Jiayu Miao, Yuanshen Lu, Kamel Hooman, Jianjun Che, Zhe Geng, Shuzhen Zhang. (2021) Experimental investigation on a novel arrangement of wet medium for evaporative cooling of air, *Internal Journal of Refrigeration* 124, 64-74. *https://doi.org/10.1016/j.ijrefrig.2020.12.01*

29. Xiangjie Chen, Yuehong Su, Devrim Aydin, Xingxing Zhang, Yate Ding, David Reay, Richard Law, Saffa Riffat. (2017) Experimental investigations of polymer hollow fibre integrated evaporative cooling system with the fibre bundles in a spindle shape, *Energy and Buildings* 154, 166-174. *https://doi.org/10.1016/j.enbuild.2017.08.068*

30. M. Lata, D.K. Gupta. (2021) Experimental Investigation and Simulation of Modified Evaporative Cooling System, in *Advances in Mechanical Engineering*, Singapore, Springer, pp. 441-448. *https://doi.org/10.1007/978*

31. *AirCare Wicking Filters*. *https://www.aircare.com/wicking-filters/*. (Accessed Apr 2023)

32. Weichao Yan, Xiangzhao Meng, Xin Cui, Yilin Liu, Qian Chen, Liwen Jin. (2022) Evaporative cooling performance prediction and multi-objective optimization for hollow fiber membrane module using response surface methodology, *Applied Energy* 325. *https://doi.org/10.1016/j.apenergy.2022.119855*

ABOUT STUDENT AUTHOR

Michael Wilkins is a mechanical engineering major student and will graduate in Spring of 2023. He will continue into a career in the HVAC industry as a manufacturing engineer and continue research in related fields.

PRESS SUMMARY

This study reviews current literature on direct evaporative cooling and how predictive modeling is derived. The thermodynamics properties, evaporative cooling media, and types of models discussed aim to provide insight in future research efforts as to the most common and effective practices. Consistency among research allows for advancements in evaporative cooling technologies at a much faster rate.