Journal of Contemporary Technology and Applied Engineering (JCTAE)

Home Page: https://jctae.journals.ekb.eg/
Published by: Faculty of Engineering, Kafrelsheikh University

Volume: 4 **Issue:** 1 **Year:** 2025
Pages: 118 - 131
DOI: 10.21608/jctae.2025.385991.1056

Print ISSN: 2812-5797
Online ISSN: 2812-5800

THEORETICAL AND CFD MODELING OF HUMIDIFICATION-DEHUMIDIFICATION (HDH) DESALINATION SYSTEMS: A COMPREHENSIVE REVIEW OF METHODOLOGIES, CHALLENGES, AND FUTURE DIRECTIONS

Received: 17-05-2025
Accepted: 23-05-2025

Mahmoud M. Othman, Fadl A. Essa*, Maher M. Abou Al-Sood, Z. M. Omara

Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh 33516, Egypt
*Corresponding author: F. A. Essa (fadlessa@eng.kfs.edu.eg) - ORCID: 0000-0002-3446-1695

ABSTRACT. The sustainable management of water resources represents a critical global challenge. In this context, HDH desalination is gaining attention as a sustainable solution for freshwater production, especially in decentralized and low-energy applications. This review provides a comprehensive analysis of humidification-dehumidification (HDH) desalination systems with a particular focus on theoretical (mathematical) and computational fluid dynamics (CFD) modeling approaches. The study reviews the fundamental working principles of HDH systems, including various configurations and thermodynamic aspects, before delving into mathematical modeling techniques ranging from analytical to numerical methods. It further explores CFD's role in resolving complex heat and mass transfer phenomena within HDH units, highlighting the capabilities and limitations of current CFD practices. A comparative evaluation between theoretical and CFD models is presented, emphasizing their applications in system design, performance prediction, and optimization. The review also identifies existing challenges and research gaps, offering insights into future advancements in HDH modeling through hybrid and AI-assisted approaches. Overall, this study aims to aid researchers and engineers in selecting appropriate modeling strategies for efficient and optimized HDH desalination systems.

KEYWORDS: HDH; Heat and mass transfer; Mathematical Modeling; CFD; AI-Assisted Simulation.

NOMENCLATURES

Symbol/Abbreviation	Description
CFD	Computational Fluid Dynamics
GOR	Gained Output Ratio
NTU	Number of Transfer Units
HDH	Humidification-Dehumidification
URF	Under-Relaxation Factors
VOF	Volume of Fluid method
STEC	Specific Thermal Energy Consumption
ρ	Fluid density (kg/m³)
u	Velocity (m/s)
S	Source term (e.g., for heat, mass, or momentum)
h	Specific enthalpy (J/kg)
k	Thermal conductivity (W/m·K) or Turbulent kinetic energy (depending on context)
T	Temperature (K or °C)
P	Pressure (Pa)
μ	Dynamic viscosity (Pa·s)
xi	Mass fraction of species i
Q	Heat transfer rate (W)
D_i	diffusion coefficient (m²/s)

1. INTRODUCTION

Freshwater scarcity has become a critical global issue due to rapid population growth, industrialization, and climate change. Today, 1.42 billion people – including 450 million children – live in areas of high or extremely high water vulnerability. Less than 3 per cent of the world's water resources is freshwater, and it is growing increasingly scarce [1].

Some facts about water scarcity [2]

- 703 million people — 1 in 11 people worldwide — lack access to clean water.
- 2.2 billion people do not have access to safely managed drinking water services.
- Women and girls around the world spend an estimated 250 million hours carrying water every day, walking on average 6 kilometers (about 3.7 miles) daily to haul 44 pounds of water.
- More than 1,000 children under 5 die every day from diseases related to lack of clean water, sanitation, and hygiene (WASH).
- 1.69 billion people live without access to adequate sanitation, and 419 million people still practice open defecation.

In Egypt, the situation is particularly critical. According to the Irrigation Minister, Egypt suffers from severe water scarcity, with only 1.3 billion cubic meters of rainfall annually. In contrast, upstream Nile Basin states receive 1,600 billion cubic meters, of which less than 3% reach downstream countries like Egypt. This highlights the urgent need for alternative freshwater sources.

Desalination methods can be categorized based on the approach used to extract freshwater. The two primary types are thermal and membrane-based technologies. Membrane desalination relies on electrical energy to operate high-pressure pumps or create an electric field, facilitating ion separation and freshwater production. In contrast, thermal desalination involves heating seawater or brine to produce vapor, which is then condensed to yield purified water (distillate) [3–6].

Among promising alternatives, humidification-dehumidification (HDH) desalination has gained attention for its ability to operate at small scales using low-grade thermal energy (e.g., solar, waste heat) [7]. Unlike conventional methods like reverse osmosis (RO) [8] or multi-stage flash (MSF) [9]. HDH systems have garnered significant attention as a promising solution for decentralized and renewable-energy-driven applications, owing to their modularity, relatively simple construction, and ability to operate effectively at low temperatures (typically 50–90°C) [10,11]. HDH desalination mimics the natural hydrological cycle, making it particularly suited for integration with solar thermal collectors and waste heat sources [12].

Despite decades of experimental and theoretical research, HDH systems continue to face critical challenges related to energy efficiency, freshwater yield, and scalability [13]. These limitations largely arise from incomplete understanding and modeling of the underlying heat and mass transfer phenomena, particularly in complex multiphase environments encountered within humidifiers and dehumidifiers [14].

Theoretical models such as thermodynamic equilibrium analyses, pinch point methodology, and the effectiveness–Number of Transfer Units (NTU) approach—have been widely applied to predict the performance of HDH cycles [15]. However, these methods often rely on simplifying assumptions, including uniform fluid distribution, negligible droplet entrainment, idealized heat and mass exchangers, and constant specific heats, which may not accurately capture real operational conditions. As a result, deviations between theoretical predictions and experimental data remain significant, especially under non-ideal or scaled-up configurations.

Parallel to theoretical developments, computational fluid dynamics (CFD) has emerged as a powerful tool for resolving the spatial and temporal variations in temperature, humidity, and velocity fields within HDH components [16,17]. CFD enables detailed simulation of complex physical processes such as droplet evaporation, vapor–liquid interfacial transport, and filmwise condensation. Nevertheless, several key gaps persist in CFD applications for HDH systems:

- **Limited Validation of Multiphase Models**: A majority of CFD studies have concentrated on either single-phase or simplified two-phase flows, often neglecting critical phenomena like droplet breakup in spray humidifiers, entrainment effects, and condensation dynamics on cold surfaces [18].
- **Integration Gaps**: There remains a lack of comprehensive studies that seamlessly couple system-level thermodynamic modeling with component-level CFD analyses, leading to disjointed optimization strategies and missed opportunities for holistic system improvements [17,18].

Sebastia-Saez et al. developed a meso-scale CFD model to investigate the complex multiphase flow behavior within structured packings, primarily applied to post-combustion CO_2 capture. Their study extends beyond conventional dry pressure drop analysis by incorporating gas–liquid interface tracking, allowing for the detailed prediction of hydrodynamic parameters such as liquid hold-up and interfacial area, which are critical for mass transfer processes. The Volume of Fluid (VOF) method was employed to track the gas–liquid interface and account for interfacial phenomena on realistic commercial geometries [19].

Kumara and Veershetty presented a theoretical investigation of a solar-powered humidification-dehumidification (HDH) desalination system designed for the climatic conditions of Surathkal, India. The system integrates a parabolic trough solar collector (PTSC) for water heating and a double-pass flat plate solar air heater for air heating, operating on a closed-air, open-water configuration. The authors developed a mathematical model incorporating energy and mass balance equations for each component (solar heaters, humidifier, dehumidifier, and storage tank), solved numerically using the 4th order Runge-Kutta method [20].

These complementary approaches—mathematical modeling for system-level analysis and CFD for detailed flow-level visualization—highlight the breadth of tools available for evaluating and improving HDH desalination systems.

This review focuses on mathematical and CFD models, analyzing their methodologies, applications, and comparative effectiveness in system design and performance evaluation. This review focuses on three key aspects of HDH systems: mathematical modeling, computational fluid dynamics (CFD) simulation, and energy/thermodynamic analysis. The objective is to assess how these approaches contribute to understanding, designing, and optimizing HDH desalination systems.

2. Fundamentals of HDH Systems

Humidification-Dehumidification (HDH) desalination is a thermally driven process that emulates the natural hydrological cycle. It operates by first humidifying air through contact with heated saline water and then condensing the moisture to obtain fresh water. The process is particularly attractive for small to medium-scale applications in remote or arid regions due to its compatibility with low-grade thermal energy sources such as solar collectors and waste heat recovery systems [21].

2.1. Basic Working Principle

An HDH system typically consists of two primary components: the **humidifier**, where air is brought into contact with hot saline water to absorb moisture, and the **dehumidifier**, where the moisture-laden air is cooled to condense water vapor into liquid form. The process relies on the thermodynamic interactions of heat and mass transfer between air and water streams [22].

During humidification, unsaturated air gains moisture and energy from the heated brine, becoming warm and humid. In the dehumidification phase, the air is cooled, and water vapor condenses to form distillate. The latent heat released during condensation can be partially recovered, enhancing overall system efficiency [23].

2.2. Thermodynamic Aspects

HDH systems are governed by psychometric principles and thermodynamic balances. Key parameters influencing system behavior include [15,24,25]:

- **Humidity ratio** and **enthalpy** of the air stream
- **Temperature gradient** between air and water streams
- **Specific heat capacities** and latent heat of vaporization
- **Air and water flow rates**

The efficiency of HDH systems is often evaluated using the **Gained Output Ratio (GOR)** and **Specific Thermal Energy Consumption (STEC).** Higher GOR values indicate more effective utilization of thermal energy [26].

Advanced models and numerical simulations (e.g., CFD) have shown that optimal performance can be achieved by carefully tuning these parameters [18].

3. Theoretical (Mathematical) Modeling Approaches

The theoretical modeling of HDH desalination systems enables the prediction and enhancement of system performance by simulating heat and mass transfer mechanisms. Models are typically developed using governing thermodynamic equations and are solved using analytical or numerical techniques. These models aid in understanding complex system interactions and serve as tools for design, optimization, and performance evaluation.

3.1. Common Assumptions

At the core of HDH modeling are mass and energy balance equations applied to both the air and water streams. The mass balance focuses on the humidity ratio and water content, while the energy balance accounts for sensible and latent heat transfer between the streams. These equations are often expressed in differential form for distributed parameter models or as algebraic expressions in lumped models [27,28]

Common assumptions in HDH modeling include [29,30]**:**

- Steady-state operation.
- Ideal gas behavior for air–water vapor mixtures.
- Negligible heat loss to the environment.
- Uniform temperature and humidity distributions at inlets.
- Constant physical properties of air and water.

These assumptions enable simplified yet effective models that capture the primary heat and mass transfer phenomena.

3.2. Analytical vs. Numerical Models

Humidification–dehumidification (HDH) desalination systems have been modeled using both analytical (closed-form or lumped-parameter) approaches and detailed numerical simulations. Analytical models typically solve simplified heat and mass balances (often one-dimensional) under idealized assumptions. For example, A. Eslamimanesh et al. developed a mass- and energy-balance computer model of a direct-contact HDH unit and found that the predicted effects of operating parameters (air and water flow rates, temperatures, etc.) [31]. These models are computationally lightweight and can be implemented using spreadsheets or basic numerical tools. However, they rely on simplifying assumptions (uniform temperature or humidity profiles, ideal counter-current flow, etc.), which can limit their accuracy. Indeed, Huang et al. noted that “existing models are not fully applicable” for detailed humidifier heat/mass transfer and report that a more advanced analytical model was needed to achieve errors below 4% [32]. In summary, analytical HDH models are computationally efficient and easy to use for simple configurations, but they may sacrifice some fidelity when spatial non-uniformities or non-ideal behavior are important.

Numerical models, by contrast, discretize the governing equations (e.g. via finite-difference, finite-volume or CFD methods) to capture detailed spatial variations. For instance, Sirine Saidi et al. formulated the full heat–mass balance equations for an integrated solar HDH unit and solved them numerically with MATLAB. Using a finite-difference discretization, they obtained results that showed “acceptable agreement” with experiments [33]. Such numerical simulations can incorporate realistic geometry, non-uniform flow, heat losses, and humidity profiles, making them much more flexible. The trade-off is higher computational cost: solving discretized PDEs requires iterative solvers and more computation time, especially for 2D/3D models. In practice, numerical HDH models are more accurate when calibrated and validated (as in the above study), but they require detailed input data (geometry, material properties, mesh resolution, etc.) and longer run times. In comparative terms, the two approaches offer complementary strengths. Analytical (or semi-analytical) models are fast and resource-light, well suited for initial design studies, sensitivity analyses, or control-oriented modeling. Numerical models are more accurate and general, capable of handling complex geometries and detailed physics, but they incur a larger computational cost. For example, an analytical 1D model might assume a uniform packed column, whereas a numerical CFD model can simulate an irregular tray or complex packing. The choice depends on the goal: one may begin with a simple analytical model for feasibility and then switch to a numerical simulation for detailed design or when dealing with non-ideal effects. In practice, many studies use a combination: using balance equations with a small number of control volumes as an “analytical” model and validating/refining it with a finer numerical solution as needed. Table 1 provide comparative terms between Analytical and Numerical Modeling.

3.3. Comparative Overview of Mathematical Modeling Studies in HDH Desalination System:

In recent years, various analytical and numerical models have been developed to analyze and optimize Humidification–Dehumidification (HDH) desalination systems. These models differ in terms of their formulation, system configuration, solution techniques, and level of validation. Table 2 presents a detailed comparative summary of significant studies, highlighting their technical approaches, numerical methods, and key findings.

Critical Insights and Thematic Analysis: The comparative evaluation of mathematical models reveals a recurring trade-off between simplicity and accuracy. Analytical models, while computationally efficient, often rely on overly idealized assumptions—such as uniform flow fields and neglect of energy losses—which limit their applicability in practical systems. Conversely, numerical models offer higher fidelity through spatial discretization but are computationally intensive and data-dependent.

Across recent studies, a key pattern emerges: hybrid modeling approaches that integrate analytical simplicity with numerical flexibility are gaining traction. For example, models that start with a simplified formulation for initial design and evolve into detailed simulations for optimization provide both agility and depth. Moreover, studies are increasingly incorporating thermoeconomic parameters (e.g., cost per liter, energy use) alongside performance metrics such as GOR, reflecting a shift toward practical applicability.

However, the lack of dynamic modeling in most works points to a critical research gap. Nearly all reviewed models assume steady-state operation, which is not representative of real-world, solar-driven, or transient-load HDH systems. Future work should prioritize transient, control-oriented, and multiscale models that can bridge the gap between theoretical feasibility and operational reliability.

Table 1. Comparison between Analytical and Numerical Modeling in HDH Desalination Systems.

Criteria	Analytical Modeling	Numerical Modeling
Accuracy	Moderate; depends on simplifying assumptions (e.g., uniform profiles)	High; captures detailed spatial and thermodynamic variations
Computational Cost	Low; fast to run and easy to implement	High; requires iterative solvers and more computational resources
Flexibility	Limited; suited to idealized geometries and flow conditions	High; applicable to a wide range of geometries and boundary conditions
Applicability to Complex Geometries	Poor; often assumes 1D or simplified systems	Excellent; can model 2D/3D, irregular or packed geometries
Required Input Data	Minimal; uses average or bulk parameters	Extensive; requires geometry, meshing, boundary and initial conditions
Ease of Implementation	Easy; can be done in Excel or simple code (e.g., MATLAB)	Complex; often requires specialized software (e.g., CFD tools, numerical solvers)
Use Case	Initial design, parametric studies, control strategies	Detailed design, validation, and capturing non-idealities
Example Study	[31]	[33]

4. Role of CFD in Desalination

4.1. Why CFD? Visualization and Detailed Local Analysis

CFD enables precise simulation of fluid dynamics, heat/mass transfer, and turbulence in HDH systems, offering insights into localized phenomena (e.g., droplet evaporation, condensation rates) that are challenging to measure experimentally. It allows virtual prototyping, reducing costs and time compared to physical testing while providing high-resolution spatial data for optimizing geometries and operating conditions [38].

Computational Fluid Dynamics (CFD) addresses the governing equations—comprising a set of coupled, nonlinear differential equations that represent conservation laws—by transforming them into algebraic equations through discretization, which is then solved using digital computing. Common discretization techniques employed in CFD simulations include the finite volume method (FVM), finite difference method (FDM), and finite element method (FEM), with FVM and FDM being the most frequently used in commercial software. The continuous advancement in computer technology has significantly contributed to the growing popularity of CFD and numerical heat transfer methods for analyzing detailed flow behavior and heat and mass transfer phenomena across various applications. Unlike experimental approaches, which can be costly and time-consuming, CFD simulations offer a more cost-effective alternative. Additionally, CFD allows for the extraction of detailed data such as flow patterns, temperature fields, and concentration distributions—information that is often challenging to capture through experiments. As a powerful analytical tool, CFD also enables flexible and user-defined modifications to operational parameters, geometry, and thermophysical properties [39].

4.2. Typical CFD Software

CFD simulations in HDH desalination commonly utilize commercial tools like ANSYS Fluent, which offers robust solvers and built-in Multiphysics capabilities, and OpenFOAM, an open-source platform providing flexibility and extensive libraries for custom solvers. Other software such as COMSOL Multiphysics and STAR-CCM+ are also employed depending on the complexity and coupling requirements of thermal, fluid, and species transport.

4.3. GOVERNING EQUATIONS AND MODELS USED

CFD models for HDH desalination systems solve coupled partial differential equations describing fluid flow, heat transfer, and species transport [40]. These equations are discretized and solved iteratively using numerical methods (e.g., finite volume).

4.3.1. Conservation Equations

1. **Mass Conservation (Continuity Equation):**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = S_m$$

ρ: fluid density (kg/m³)

u: velocity vector (m/s)

S_m: mass source term (e.g., due to evaporation or condensation)

2. **Momentum Conservation (Navier–Stokes Equations)**

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u \otimes u) = -\nabla p + \nabla \cdot (\mu \nabla u) + \rho g + F$$

p: pressure (Pa)

μ: dynamic viscosity (Pa·s)

g: gravitational acceleration

F: external body forces (e.g., drag in porous media)

3. **Energy Conservation**

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho u h) = \nabla \cdot (k \nabla T) + S_h$$

h: specific enthalpy (J/kg)

T: temperature (K)

k: thermal conductivity (W/m·K)

S_h: source term from heat transfer or phase change

4.3.2. Species Transport Equation

$$\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho u Y_i) = \nabla \cdot (D_i \nabla Y_i) + S_i$$

Y_i: mass fraction of species i (e.g., water vapor, air)

D_i: diffusion coefficient (m²/s)

S_i: source term (e.g., evaporation rate)

4.3.3. Turbulence Models [41]

In CFD modeling of HDH desalination systems, turbulence plays a significant role due to the typically high Reynolds number flows of air and water within humidifiers and dehumidifiers. Turbulence models are essential to capture complex fluid motion and enhance the accuracy of heat and mass transfer predictions. The standard $k-\varepsilon$ model is one of the most widely used models because of its simplicity and robustness. It solves two transport equations: one for the turbulent kinetic energy (k) and another for its dissipation rate (ε). However, it may provide less accurate results in flows with strong pressure gradients or near-wall regions. To overcome these limitations, the Shear Stress Transport (SST) $k-\omega$ model is often preferred in HDH applications. This model combines the near-wall precision of the $k-\omega$ model with the free-stream independence of the $k-\varepsilon$ model, allowing for better prediction of flow separation, mixing, and boundary layer behavior. These turbulence models are crucial for resolving detailed local variations in velocity, temperature, and humidity, which directly affect evaporation and condensation rates in the system. The selection of an appropriate turbulence model depends on the specific geometry, operating conditions, and required accuracy of the simulation.

4.4. BOUNDARY CONDITIONS AND CONVERGENCE STRATEGIES [42–44]

4.4.1. Boundary Conditions

Accurate boundary condition (BC) specification is essential to ensure physical fidelity in HDH CFD models.

1. **Inlet Conditions**

Inlet BCs are generally defined as velocity or mass-flow inlets, where the velocity (or mass flow rate), temperature, and species mass fractions (e.g., water vapor and dry air) must be prescribed. Turbulence quantities such as turbulent kinetic energy and dissipation (or specific dissipation rate) are commonly initialized using turbulence intensity and hydraulic diameter relationships. For spray or droplet applications, a discrete phase model (DPM) inlet with a droplet size distribution (e.g., Rosin–Rammler [45]) can be specified to represent spray injection.

2. **Outlet Conditions**

Pressure outlets are widely used at exhaust boundaries, where a fixed static pressure (often ambient) is applied and backflow conditions for temperature and species are defined to prevent non-physical reflections. In cases of well-developed flow, an outflow (zero diffusive flux) condition may be used instead, particularly when recycling is minimal.

3. **Wall Conditions**

Solid walls employ the no-slip condition for velocity and can be set as adiabatic or with specified heat flux/temperature depending on insulation or heating requirements. In conjugate heat transfer analyses, wall thickness and material conductivity are included to solve both fluid and solid domains together.

4. Species Transport and Porous Media

For multicomponent flows, species mass fractions at inlets and zero-gradient conditions at outlets maintain correct mass conservation. Packed beds are modeled via porous‑jump or Darcy‑Forchheimer formulations to capture pressure drop and momentum loss within the bed.

4.4.2. Convergence Strategies

Ensuring numerical stability and physical accuracy requires careful convergence management.

1. Residual Monitoring:

Residuals quantify the local imbalance in each transport equation. Typical convergence targets are on the order of 10^{-3} for continuity and momentum and 10^{-5} for energy and species equations LEAP Australia Pty Ltd. However, residuals alone can be misleading; they mainly indicate divergence rather than true convergence SimScale.

2. Under-Relaxation Factors (URFs):

URFs limit the change in solution variables per iteration. Lowering momentum URFs (e.g., to 0.3–0.7) stabilizes strongly coupled flows, while higher URFs for energy (0.7–1.0) accelerate thermal convergence. Care must be taken overly low URFs can mask divergence and produce flat residual curves without true convergence.

3. Mesh Independence Study:

A mesh-independence study involves running simulations on increasingly refined meshes until key outputs (e.g., temperature, humidity ratio, pressure drop) change by less than a pre-defined tolerance (often <1%). Finer meshes reduce numerical diffusion but can be harder to converge, so refinement should focus on critical regions (e.g., near walls, inlets) CFD-online.com.

4. Initialization Techniques

Good initial guesses accelerate convergence. Techniques include hybrid initialization (in Fluent) or potentialFoam (in OpenFOAM) for steady-state problems, and pseudo-transient ramping of under-relaxation factors to avoid poor initial conditions DMS Online. Starting with a coarser mesh or lower Reynolds number can also help bootstrap convergence for complex geometries.

4.5. Comparative Overview of CFD Studies in HDH Desalination System

Table 3 presents a comparative analysis of some CFD studies focusing on humidification–dehumidification (HDH) desalination systems. Each study is evaluated based on system configuration, CFD methodologies, validation approaches, and key findings. This compilation aims to provide insights into the diverse modeling techniques and performance outcomes associated with HDH desalination research.

Critical Insights and Thematic Analysis: The CFD studies reviewed in this work reveal a substantial evolution in modeling sophistication—from early single-phase approximations to recent multiphase, turbulence-resolved simulations. A notable trend is the increasing use of VOF (Volume of Fluid) and DPM (Discrete Phase Models) to capture droplet dynamics and condensation in humidifiers and dehumidifiers.

Despite this progress, several limitations persist. Validation against experimental data is often partial or absent, making it difficult to assess the reliability of predictions, especially when extrapolated to full-scale systems. Only a few studies conduct mesh independence and sensitivity analyses, which are essential for ensuring numerical accuracy. Moreover, the high computational cost of multiphase CFD restricts its use in iterative optimization or design studies.

There is a growing need for reduced-order CFD models or surrogate modeling using AI to speed up simulations without compromising fidelity. Furthermore, very few studies have attempted to couple CFD with system-level thermodynamic models, leaving a disconnection between localized physics and global performance indicators. Addressing this integration gap is essential for creating holistic design frameworks and operational strategies.

Table 2. Comparative analysis of mathematical modeling studies on HDH desalination systems

No.	***Study Focus***	***Model Type***	***Key Assumptions***	***Solution Methods***	***Performance Metrics***	***Citation***
1	Thermodynamic analysis of semi-open-air (SOA) HDH with water/air heating	Analytical + Numerical	Steady-state operation; saturated air at humidifier outlet; negligible heat losses	Energy/entropy balance equations solved iteratively with MATLAB	GOR: 2.88–3.4	[34]
2	Thermoeconomic optimization with waste heat recovery	Iterative mathematical model	Constant component effectiveness; fixed thermophysical properties 17	Multi-objective optimization using EES® software; entropy generation minimization	Production: 16% increase (June); Cost: $0.014/L	[35]
4	Air-cooling condenser with cellulose evaporative pad	Experimental + Thermodynamic modeling	Steady-state operation; saturated air at humidifier outlet; negligible heat losses	Finite volume method for heat/mass transfer; experimental validation with sensors	Condenser effectiveness: 0.53	[36]
5	HDH coupled with wet-cooling tower	Mathematical modeling + Cost analysis	Steady state operation condition; ideal heat exchanger performance	Cost-benefit analysis using MATLAB; heat exchanger pinch analysis	Freshwater cost: $3.17/m^3$; GOR = 0.685	[37]
6	Closed-air open-water (CAOW) water-heated HDH system with and without extractions.	Analytical and numerical	All processes investigated are steady state. The HDH system components and extractions are insulated. The required energy to derive pumps and blowers is neglected in comparison to the input heating energy. Potential and kinetic energies are neglected	Thermodynamic balancing "temperature pinch"	The maximum error of the present methods is about±3%.	[23]

Table 3. Comparative Analysis of CFD Studies on Humidification–Dehumidification (HDH) Desalination Systems.

#	System Configuration	CFD Software & Models	Validation Method	Key Findings	Ref
1	Evaporation and condensation in conjunction with double diffusive natural convection	The model is based on numerical solutions of the conservation equations of mass, momentum, energy and species considering the Boussinesq approximation	2 basic cases used to validate the study: • differentially heated enclosure model validation • double diffusive natural convection model validation	Maximum rate of average distillate occurring at an aspect ratio of 1.5 for the case of Rayleigh number, $Ra = 10^4$ and buoyancy ratio, N = 1	[46]
2	Combined-cooling and desalination plant dehumidifier (two-stage HDH)	ANSYS CFX 15.0 & $SST\ k-\omega$ turbulence - Free-surface multiphase (volume-of-fluid)	Compared simulated outlet air temperature, velocity, and chilled-water temperature to experiments—deviations of 0.41%, 6.45%, and –0.70%, respectively	The desalinated water produced at a hot water flow of 100 LPH is found to be 2205 ml/h from the experiments	[46]
3	Using a vortex generator to increase the rate and efficiency of evaporation in a forced-flow desalination unit.	Cradle CFD software & a grid independence test is conducted	The experiment was conducted indoors to reduce uncontrolled variables	The rate of evaporation with a vortex generator was 13% higher than that without a vortex generator, and the gained output ratio increased 14% with the vortex generator	[47]
4	Solar air humidifier & the combined effect of heating and humidifying processes in the plate type humidification chamber.	COMSOL Multiphysics	Validation of the mathematical model against experimental observations revealed a high level of consistency.	The highest evaporation rate was achieved for the narrowest channel and lowest flow rate	[40]
5	Solar photovoltaic panel (PVP) HDH system & parabolic trough collector (PTC) HDH system	OpenFOAM & finite volume method (FVM) using interCondensatingEvaporatingFoam solver for two dimensional, incompressible, non-isothermal immiscible fluids with phase- change, using volume of fraction-based interface capturing is included.	(CFD) simulations were validated using standard experimental results of the solar photovoltaic panel (PVP) HDH system reported in the literature. & Theoretical heat transfer calculations and experimental	The yield performance of the basic PVP system increased by 16% following the integration of partitions in the humidifier and fins in the dehumidified. & The improved PTC system with slope shows 18 % higher yield as	[48]

#	System Configuration	CFD Software & Models	Validation Method	Key Findings	Ref
			data from the literature were utilized to validate the CFD investigations of the PTC humidifier and dehumidifier	compared to the improved PVP system.	
6	Condensation of water vapor present in humid air on a cold surface in the dehumidifier for water desalination	Ansys CFX & Wall Condensation Model	in the dehumidifier for water desalination for validation & The water output results from the CFD simulations agree with reference values, with deviations ranging from 2.5% to 10% across inlet temperatures between 44 °C and 54 °C.	The downstream fins are less efficient for water condensation as they predominantly cool the air; hence, rearranging them in parallel is suggested to increase the water output.	[17]
7	Novel tray humidifier column for HDH desalination	ANSYS Inc (FLUENT) & A two-phase model was provided in the framework of VOF at unsteady state condition	The performance of the humidifier column was evaluated using both experimental methods and CFD simulations, with an average deviation of 6% observed between the two approaches	The humidifier effectiveness of the tray humidifier column varies between 0.67 and 0.87	[18]
8	HDH counter-current direct contact evaporator	ANSYS Fluent & The evaporation model is based on a first-order approximation of Fick's first law at the inter-face between gas and liquid	There are previous experimental studies that lead to this work,	The study revealed a strong dependence on water spray density, particularly up to the point where it matches the corrugation density of the column. Under the tested conditions with the Lantec HD-QPAC, the system exhibited minimal sensitivity to variations in gas distribution.	[49]

5. CHALLENGES AND RESEARCH GAPS

Despite significant progress in modeling HDH desalination systems, several challenges and research gaps persist:

1) Experimental Validation Deficiency: A majority of CFD studies are validated against limited experimental data or simplified configurations, leading to uncertainties when scaling up or applying to real-world systems. Comprehensive experimental datasets for multiphase flow dynamics, droplet behavior, and condensation phenomena are still lacking.
2) High Computational Demands: Detailed CFD simulations involving multiphase interactions, turbulence modeling, and fine meshing require substantial computational resources and time, limiting their feasibility for large-scale or real-time applications.
3) Integration of Multiscale Models: Current research often treats system-level thermodynamic models and component-level CFD simulations separately. There is a critical need for integrated frameworks that couple both scales for holistic design and optimization.
4) Dynamic and Transient Analysis Gaps: Most models assume steady-state conditions, overlooking transient behaviors, start-up dynamics, and operational variations, which are essential for practical applications.
5) AI and Machine Learning Integration: The application of AI/ML in accelerating CFD simulations, optimizing designs, and developing predictive models is still in its infancy for HDH systems, representing a promising area for future research.

6. CONCLUSIONS AND FUTURE OUTLOOK

Mathematical and CFD models are indispensable tools for understanding, designing, and optimizing HDH desalination systems. Theoretical models offer quick and efficient preliminary analyses, while CFD provides detailed insights into complex heat and mass transfer phenomena. Both approaches complement each other and should be used synergistically to achieve accurate and reliable performance predictions.

Looking forward, several key future modifications and research directions should be addressed to advance the field:

- Development of integrated multiscale models that couple system-level thermodynamics with component-level CFD simulations to enable holistic design and optimization.
- Expansion of transient and dynamic analysis, which is essential for modeling real-world operational conditions, startup processes, and control strategies in HDH systems.
- Wider adoption of AI and machine learning methods to create surrogate models for rapid optimization, real-time control, and predictive maintenance of HDH systems.
- Reduction in computational costs through hybrid modeling techniques, adaptive mesh refinement, and reduced-order models that maintain accuracy with less computational demand.
- Strengthening experimental validation, especially for multiphase flow, droplet dynamics, and condensation, to improve the credibility and applicability of CFD results.
- Investigation into novel materials and heat exchanger designs that can improve the thermal performance and energy recovery efficiency in humidifiers and dehumidifiers.

Future research should prioritize these directions to enhance the accuracy, efficiency, and scalability of HDH modeling, ultimately supporting the deployment of sustainable and decentralized water desalination technologies.

ACKNOWLEDGEMENTS

This paper is based upon work supported by Science, Technology & Innovation Funding Authority (STDF) under grant number 51018.

REFERENCES

[1] Wash R. Water security for all. Water Well J 2002;56:58.

[2] Reid K. Global water crisis: Facts, FAQs, and how to help | World Vision. World Vis 2018. https://www.worldvision.org/clean-water-news-stories/global-water-crisis-facts (accessed May 28, 2023).

[3] Essa FA, Abdullah AS, Omara Z. Enhancement of pyramid solar distiller performance using thermal storage material. J Contemp Technol Appl Eng 2023;2:56–64. https://doi.org/10.21608/jctae.2023.233154.1016

[4] Younes M, Alawee WH, Abdullah AS, Omara Z, Essa FA. Techniques used to reduce back wall losses of solar stills - A review. J Contemp Technol Appl Eng 2022;1:62–74. https://doi.org/10.21608/jctae.2022.158802.1008.

[5] Essa FA, Abdullah AS, Alqsair U, Alawee WH, Omara Z, Younes M. Testing the trays solar stills with yellow sand beds and reflectors. J Contemp Technol Appl Eng 2022;0:0–0. https://doi.org/10.21608/jctae.2022.158806.1009.

[6] Alawee WH, Omara ZM. Integrating A Vertical Wick Solar Still To Enhance Pyramid Solar Still Production,2024;3:88–93. https://doi.org/10.21608/JCTAE.2024.303054.1032.

[7] Daylan B, Ciliz N. Life cycle assessment and environmental life cycle costing analysis of lignocellulosic bioethanol as an alternative transportation fuel. Renew Energy 2016;89:578–87. https://doi.org/10.1016/j.renene.2015.11.059.

[8] Essa FA, Elaziz MA, Al-Betar MA, Elsheikh AH. Performance prediction of a reverse osmosis unit using an optimized Long Short-term Memory model by hummingbird optimizer. Process Saf Environ Prot 2023;169:93–106. https://doi.org/10.1016/j.psep.2022.10.071.

[9] Al-Othman A, Tawalbeh M, El Haj Assad M, Alkayyali T, Eisa A. Novel multi-stage flash (MSF) desalination plant driven by parabolic trough collectors and a solar pond: A simulation study in UAE. Desalination 2018;443:237–44. https://doi.org/10.1016/j.desal.2018.06.005.

[10] Irrigation Minister: Egypt suffers from water scarcity, drought-SIS n.d. https://sis.gov.eg/Story/196381/Irrigation-Minister-Egypt-suffers-from-water-scarcity%2C-drought?lang=en-us (accessed April 11, 2025).

[11] Mistry KH, McGovern RK, Thiel GP, Summers EK, Zubair SM, Lienhard JH. Entropy generation analysis of desalination technologies. Entropy 2011;13:1829–64. https://doi.org/10.3390/e13101829.

[12] Essa FA, Othman MM, Abdullah AS, Abou Al-Sood MM, Omara ZM. Critical issues on advancements and challenges in HDH desalination units. Results Eng 2024;22:102180. https://doi.org/10.1016/j.rineng.2024.102180.

[13] Fath HES. Solar distillation: a promising alternative for water provision with free energy, simple technology and a clean environment. Desalination 1998;116:45–56. https://doi.org/https://doi.org/10.1016/S0011-9164(98)00056-3.

[14] Kabeel AE, Diab MR, Elazab MA, El-Said EMS. Different configuration comparisons for hybrid solar desalination systems: process and performance analyses. Int J Energy Water Resour 2023;7:437–52. https://doi.org/10.1007/s42108-022-00220-1.

[15] Narayan GP, Sharqawy MH, Lienhard V JH, Zubair SM. Thermodynamic analysis of humidification dehumidification desalination cycles. Desalin Water Treat 2010;16:339–53. https://doi.org/10.5004/dwt.2010.1078.

[16] Saeed A, Antar MA, Sharqawy MH, Badr HM. CFD modeling of humidification dehumidification distillation process. Desalination 2016;395:46–56. https://doi.org/10.1016/j.desal.2016.03.011.

[17] Patel V, Patel R, Trapasia N, Patel V. CFD Simulation of Dehumidification of Air in Humidification-Dehumidification based Water Desalination System. Iran J Sci Technol - Trans Mech Eng 2022;46:449–63. https://doi.org/10.1007/s40997-021-00454-0.

[18] Zarei T, Jahromi RH, Karachi AM. Experimental and computational fluid dynamics modeling of a novel tray humidifier column in humidification dehumidification desalination; evaluation of hydrodynamic and heat transfer characteristics. Proc Inst Mech Eng Part E J Process Mech Eng 2020;234:275–84. https://doi.org/10.1177/0954408920916580.

[19] Sebastia-Saez D, Gu S, Ranganathan P, Papadikis K. Meso-scale CFD study of the pressure drop, liquid hold-up, interfacial area and mass transfer in structured packing materials. Int J Greenh Gas Control 2015;42:388–99. https://doi.org/10.1016/j.ijggc.2015.08.016.

[20] Kumara, Veershetty G. Humidification Dehumidification Desalination Using Solar Collectors. IOP Conf Ser Mater Sci Eng 2018;376. https://doi.org/10.1088/1757-899X/376/1/012025.

[21] Patel V, Patel R, Trapasia N, Patel V. CFD Simulation of Dehumidification of Air in Humidification-Dehumidification based Water Desalination System. Iran J Sci Technol Trans Mech Eng 2022;46:449–63. https://doi.org/10.1007/s40997-021-00454-0.

[22] Mahmoudi A, Valipour MS, Rashidi S. Performance Enhancement Techniques in Humidification–Dehumidification Desalination Systems: A Detailed Review. J Therm Anal Calorim 2024. https://doi.org/10.1007/s10973-024-13489-7.

[23] Ahmed MA, Qasem NAA, Zubair SM. Analytical and numerical schemes for thermodynamically balanced humidification-dehumidification desalination systems. Energy Convers Manag 2019;200:112052. https://doi.org/https://doi.org/10.1016/j.enconman.2019.112052.

[24] Prakash Narayan G, Mistry KH, Sharqawy MH, Zubair SM, Lienhard JH. Energy effectiveness of simultaneous heat and mass exchange devices. Front Heat Mass Transf 2010;1. https://doi.org/10.5098/hmt.v1.2.3001.

[25] Marzouk S, Abou Al-Sood MM, El-Said E, Younes MM, El-Fakharany M. Review of passive methods of heat transfer enhancement in helical tube heat exchanger. J Contemp Technol Appl Eng 2023;2:28–52. https://doi.org/10.21608/jctae.2023.250495.1020.

[26] Khairat Dawood MM, Amer A, Teamah MA, Aref A, Mansour T. Experimental investigation of two-stage humidification-dehumidification desalination system integrated with an innovative oxy-hydrogen (HHO) system. Int J Energy Res 2021;45:9116–40. https://doi.org/10.1002/er.6442.

[27] Sharqawy MH, Antar MA, Zubair SM, Elbashir AM. Optimum thermal design of humidification dehumidification desalination systems. Desalination 2014;349:10–21. https://doi.org/10.1016/j.desal.2014.06.016.

[28] He WF, Xu LN, Han D, Gao L, Yue C, Pu WH. Thermodynamic investigation of waste heat driven desalination unit based on humidification dehumidification (HDH) processes. Appl Therm Eng 2016;100:315–24. https://doi.org/10.1016/j.applthermaleng.2016.02.047.

[29] He WF, Yang HX, Han D. Thermodynamic analysis of a novel humidification dehumidification desalination system driven by heat pump. Energy Procedia 2019;158:6030–7. https://doi.org/10.1016/j.egypro.2019.01.515.

[30] Chehayeb KM, Narayan GP, Zubair SM, Lienhard JH. Thermodynamic balancing of a fixed-size two-stage humidification dehumidification desalination system. Desalination 2015;369:125–39. https://doi.org/10.1016/j.desal.2015.04.021.

[31] Mathematical modeling of a direct contact humidification– dehumidification desalination process n.d. https://www.lenntech.com/abstracts/2521/mathematical-modeling-of-a-direct-contact-humidification-dehumidification-desalination-process.html (accessed May 2, 2025).

[32] Huang X, Chen H, Ling X, Liu L, Huhe T. Investigation of heat and mass transfer and gas–liquid thermodynamic process paths in a humidifier. Energy 2022;261:125156. https://doi.org/10.1016/j.energy.2022.125156.

[33] Saidi S, Ben Radhia R, Nafiri N, Benhamou B, Jabrallah S Ben. Numerical study and experimental validation of a solar powered humidification-dehumidification desalination system with integrated air and water collectors in the humidifier. Renew Energy 2023;206:466–80. https://doi.org/10.1016/j.renene.2023.02.048.

[34] Bacha H Ben. Thermodynamic comparison of the operation of the HDH system with water heating or air heating in closed water circulation and semi-open-air circulation. Int J Thermofluids 2024;21:100535. https://doi.org/10.1016/j.ijft.2023.100535.

[35] Tariq R, Jimenez JT, Sheikh NA, Khan S. Mathematical approach to improve the thermoeconomics of a humidification dehumidification solar desalination system. Mathematics 2021;9:1–31. https://doi.org/10.3390/math9010033.

[36] Xu L, Chen YP, Wu PH, Huang BJ. Humidification-Dehumidification (HDH) desalination system with air-cooling condenser and cellulose evaporative pad. Water (Switzerland) 2020;12. https://doi.org/10.3390/w12010142.

[37] AlQurashi, Hussain, and Adel Abdel Dayem. "A Novel Hdh Desalination System Powered by a Local Wet-Cooling Tower." Available at SSRN 4638902.

[38] Wardeh S, Morvan HP. CFD Modelling of Reverse Osmosis Channels with Potential Applications to the Desalination Industry. Chem Prod Process Model 2011;6. https://doi.org/10.2202/1934-2659.1599.

[39] Wen T, Lu L, He W, Min Y. Fundamentals and applications of CFD technology on analyzing falling film heat and mass exchangers: A comprehensive review. Appl Energy 2020;261:114473. https://doi.org/10.1016/j.apenergy.2019.114473.

[40] Al-Abbasi O, Sarac B, Ayhan T. Experimental investigation and CFD modeling to assess the performance of solar air humidifier. Int J Heat Technol 2019;37:357–64. https://doi.org/10.18280/ijht.370143.

[41] Wan T, Zhou M, Zhao P, Wang X. Challenges in the modeling and simulation of turbulent supercritical fluid flows and heat transfer. Propuls Energy 2025:1–27. https://doi.org/10.1007/s44270-024-00005-3.

[42] Computational Fluid Dynamics. Elsevier; 2018. https://doi.org/10.1016/C2015-0-06135-4.

[43] Ansys Fluent | Fluid Simulation Software n.d. https://www.ansys.com/products/fluids/ansys-fluent (accessed May 13, 2025).

[44] Simulation Software | Engineering in the Cloud | SimScale n.d. https://www.simscale.com/ (accessed May 13, 2025).

[45] Recovery R. The rosin-rammler particle size distribution. Resour Recover Conserv 1980;5:275–7.

[46] Saeed A, Antar MA, Sharqawy MH, Badr HM. CFD modeling of humidification dehumidification distillation process. Desalination 2016;395:46–56. https://doi.org/10.1016/j.desal.2016.03.011.

[47] Mugisidi D, Heriyani O. Improving the Performance of a Forced-flow Desalination Unit using a Vortex Generator. CFD Lett 2024;16:81–93. https://doi.org/10.37934/cfdl.16.10.8193.

[48] Manimaran R. Performance assessment of solar PV and thermal-driven humidification dehumidification systems: A CFD modelling approach. Energy Convers Manag 2021;245:114574. https://doi.org/10.1016/j.enconman.2021.114574.

[49] Roy C, Klausner JF, Bénard A. Numerical study on the impact of fluid distribution on a counter-current direct contact evaporator. Int J Heat Mass Transf 2021;166. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120561.