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Design Assessment of a Locally Fabricable Air-to-Air Plate Heat Exchanger for Indirect-Direct Evaporative Cooling

Emmanuel Udama Odeh[1]
Department of Mechanical and Aerospace Engineering
University of Uyo, Uyo, Akwa Ibom State, Nigeria
Uwah Etebom Francis[2]
Department of Mechanical and Aerospace Engineering
University of Uyo, Uyo, Akwa Ibom State, Nigeria
Urua, John Dennis[3]
Department of Mechanical and Aerospace Engineering
University of Uyo, Uyo, Akwa Ibom State, Nigeria

Abstract
This study examines a locally fabricable air-to-air plate heat exchanger used as the indirect stage of an indirect-direct evaporative cooling (IDEC) system. The work uses the TRNSYS 18.0 system model and the HTRI Xchanger Suite 7.3.2 plate heat-exchanger specification reported for a low-cost solar-assisted evaporative cooling system. The selected core is a 65-plate SS304 air-to-air exchanger with 327 mm plate length, 249 mm plate height, 0.6 mm plate thickness, 4.5 mm nominal gap, 101.6 mm port diameter, 32 hot-air channels, 32 cold-air channels, countercurrent flow arrangement and 0.33 m² effective heat-transfer area per plate. The direct evaporative cooling (DEC) outlet temperature varied from 17.90 °C to 30.35 °C over the reported daily period, while the IDEC outlet temperature remained within 19.15-19.32 °C. The mean cooled-air temperature was 24.75 °C for DEC and 19.23 °C for IDEC, with corresponding mean cooling efficiencies of 64.05% and 91.30%. These results show that the plate exchanger can provide useful sensible pre-cooling and a steadier supply-air condition under warm-humid conditions in South-South Nigeria. Leakage, pressure drop, flow distribution and heat-transfer effectiveness still require prototype measurement.

Keywords: plate heat exchanger; indirect-direct evaporative cooling; TRNSYS; HTRI Xchanger Suite; cooling efficiency; warm-humid climate

1. Introduction

Warm-humid buildings in Nigeria require cooling systems that can provide acceptable indoor conditions without placing excessive demand on unreliable electricity supply. Vapour-compression air-conditioning can control temperature effectively, but its energy demand and refrigerant-related environmental burden remain important concerns for low-cost residential and institutional applications [1]-[3]. Evaporative cooling offers a simpler alternative because it uses water as the working fluid and can be supported by low-power or renewable-energy systems [4].

Direct evaporative cooling is simple and inexpensive, but it adds moisture to the supply air and its performance can fluctuate when outdoor humidity is high. Indirect-direct evaporative cooling improves this arrangement by adding a sensible heat-exchange stage before the wetted pad [5], [6]. In this layout, the primary air is first cooled across a dry plate exchanger before it reaches the direct evaporative section.

Compact plate heat exchangers are suitable for this duty because they provide a large surface area within a small core [7], [8]. Their performance depends on more than surface area. Plate spacing, leakage, flow distribution, sealing quality, pressure loss, surface condition and ease of cleaning all affect the useful cooling delivered by a fabricated unit [9]. These issues are especially important where the exchanger is expected to be produced with local fabrication methods.

This study examines the air-to-air plate heat exchanger specified for the IDEC system reported by Ozuomba [10]. It uses the same building load, operating assumptions, TRNSYS model, HTRI plate specification and

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DEC-IDEC performance values. The focus is the contribution of the plate exchanger to the cooling response of the IDEC system.

2. Materials and methods

2.1 Simulation tools and source data

The modelling chain follows Ozuomba [10]. TRNSYS 18.0 was used for system performance analysis, HTRI Xchanger Suite 7.3.2 for the plate heat-exchanger specification, Edraw Max Pro for the two-dimensional system diagrams and a Fortran F90 compiler for supporting routines. The computer platform was an Intel Core i5 system with 2.5 GHz CPU and 8 GB RAM.

2.2 Cooling-system arrangement

Two cooling configurations were considered. In DEC, ambient air passes through a wetted pad and is cooled by evaporation before delivery to the space. In IDEC, the ambient stream first passes through an air-to-air plate heat exchanger. This stage removes sensible heat without direct water contact, after which the pre-cooled air passes through the wetted pad for further cooling. The secondary stream supports heat removal across the exchanger and is vented separately.

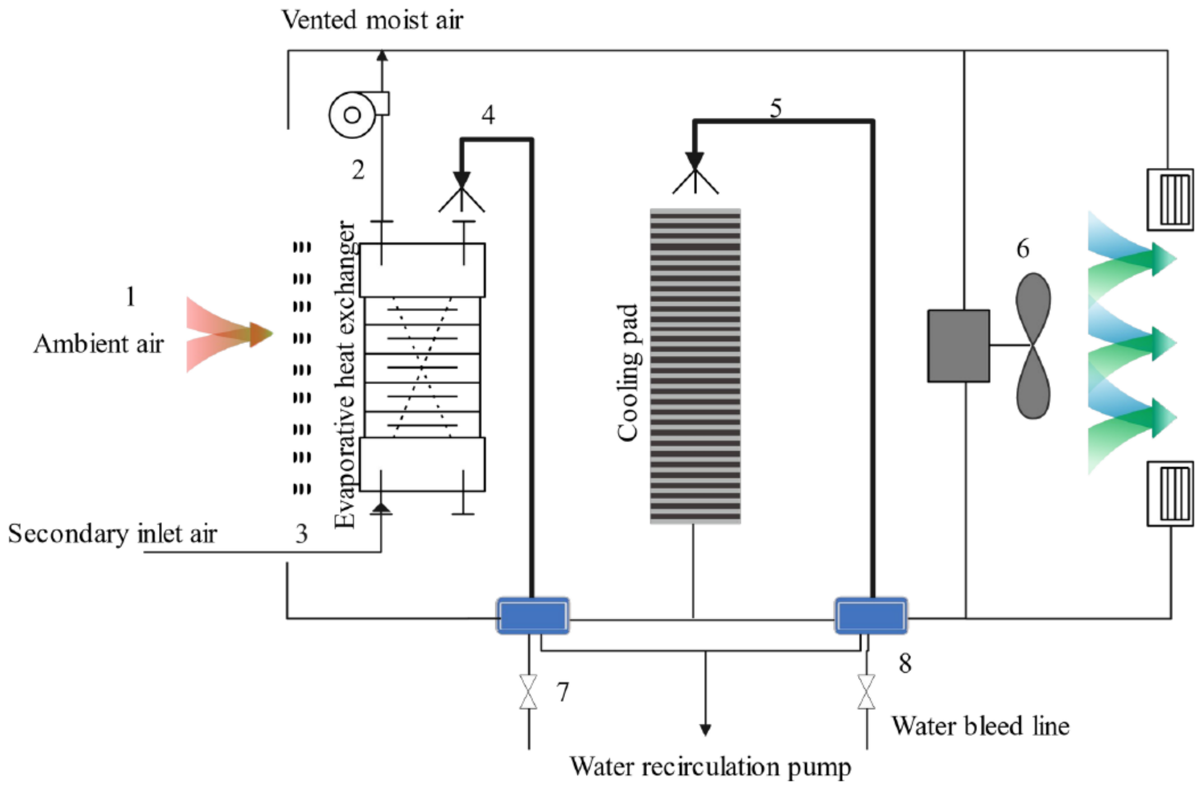

Figure 3.1b Schematic of the indirect-direct evaporative system (*Modelled with EdrawMax*

Figure 1. Indirect-direct evaporative cooling arrangement from the thesis schematic.

2.3 Study area and design conditions

The case-study facility was the Mechanical Engineering Workshop, Faculty of Engineering, University of Uyo, in South-South Nigeria. The building is a two-storey workshop and office complex at latitude 5.0361°N and longitude 7.9837°E, with a total gross area of 338.9 m² and a height of 5.64 m. Occupancy was set for weekdays from 8:00 a.m. to 4:00 p.m. The weather file used in the simulation was labelled Port Harcourt and was retained as a warm-humid South-South Nigeria reference dataset for the Uyo case study.

Table 1. Operating conditions used for the performance analysis.

Parameter	Value	Unit
Inlet primary air temperature, T1	29.4	°C

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Parameter	Value	Unit
Relative humidity, RH	76.6	%
Kinematic viscosity of air	1.593 x 10^-5	m^2/s
Inlet secondary air temperature, T2	26.01	°C
Humidity ratio	0.0199	kg/kg
Prandtl number	0.71386	-
Density of air, ρair	1.167	kg/m^3
Specific heat of air, Cpa	1.005	kJ/kg.K
Specific heat of water vapour, Cpv	1.864	kJ/kg.K
Specific heat of humid air, Cpu	1.042	kJ/kg.K

2.4 Cooling-load basis and operating assumptions

The cooling-load estimate used an outdoor design condition of 29.4 °C and 76.6% relative humidity, and an indoor design condition of 22 °C and 55% relative humidity. The walls, roof and floor were insulated with 90 mm polyurethane and a U-value of 0.49 $W/m^2.K$. Transmission gains were calculated for the envelope, while occupant, lighting and infiltration gains were added to obtain the daily load. The resulting total cooling-load requirement was 110.62 kWh/day.

Table 2. Cooling-load components used in the thesis model.

Load component	Value	Unit
Transmission heat gain	18.43	kWh/day
People-related internal load	88.56	kWh/day
Lighting load	2.40	kWh/day
Infiltration load	1.23	kWh/day
Total cooling-load requirement	110.62	kWh/day

The TRNSYS model used fluorescent lighting of 16 W/m^2 during occupied hours, ten staff occupants during use, equal supply and return ventilation flow rates of 2000 m^3/h at 22 °C, a heat-recovery-unit maximum efficiency of 80%, maximum saturation efficiencies of 70% for the supply-air humidifier and 80% for the exhaust-air humidifier, full evaporation of water into the air stream, fan heating of about 1.1 K and moisture gains from occupants. Although the occupancy schedule was 8:00 a.m. to 4:00 p.m., the reported cooling response covered 07hr00 to 22hr00 to describe the daily temperature trend.

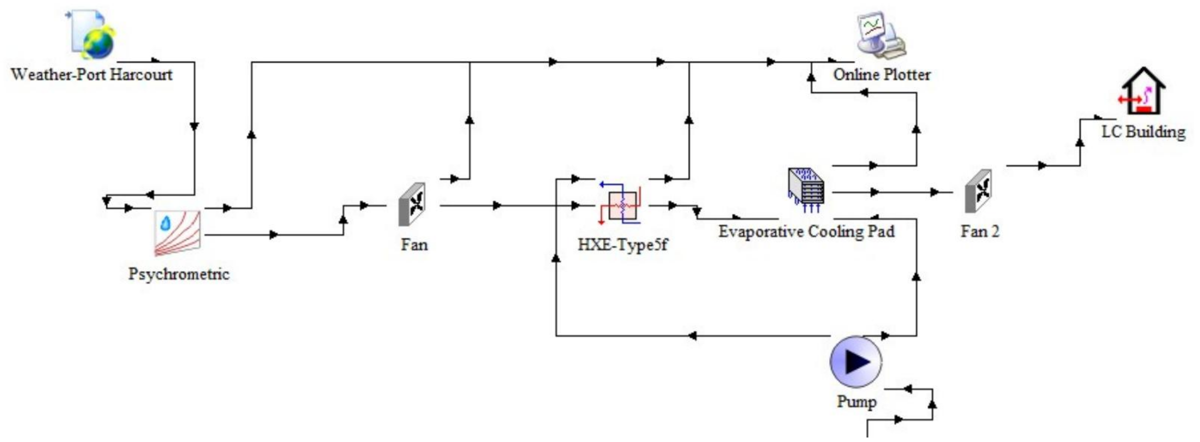

Figure 2. TRNSYS model of the indirect-direct evaporative cooling configuration.

2.5 Plate heat-exchanger specification

The plate heat exchanger was specified in HTRI Xchanger Suite 7.3.2 as an SS304 air-to-air core for the IDEC indirect stage. Stainless steel was selected for durability, cleanability and practical local fabrication. The HTRI setup used countercurrent flow, 65 plates, 32 hot-air channels, 32 cold-air channels and a nominal plate gap of 4.5 mm. The pressure entries in the HTRI design table are retained as model-input values from the original specification.

Table 3. Plate heat-exchanger specification used for the IDEC model.

Parameter	**Value**	**Unit**
Plate length, L	327	mm
Plate height, H	249	mm
Plate thickness, t	0.6	mm
Total width	363	mm
Effective heat-transfer area per plate, hT	0.33	m^2
Number of plates, N	65	-
Number of hot-air channels, Nh	32	-
Number of cold-air channels, Nc	32	-
Nominal plate gap	4.5	mm
Port diameter	101.6	mm
Flow path across plate	Parallel	-
Operating pressure input	650	kPa
Allowable pressure-drop input	120	kPa
Flow configuration	Countercurrent	-
Tightened packed length	327	mm

The pressure entries in Table 3 are HTRI model inputs retained from the original specification. Airflow-side pressure loss for the fabricated core should be reported separately in Pa after prototype testing.

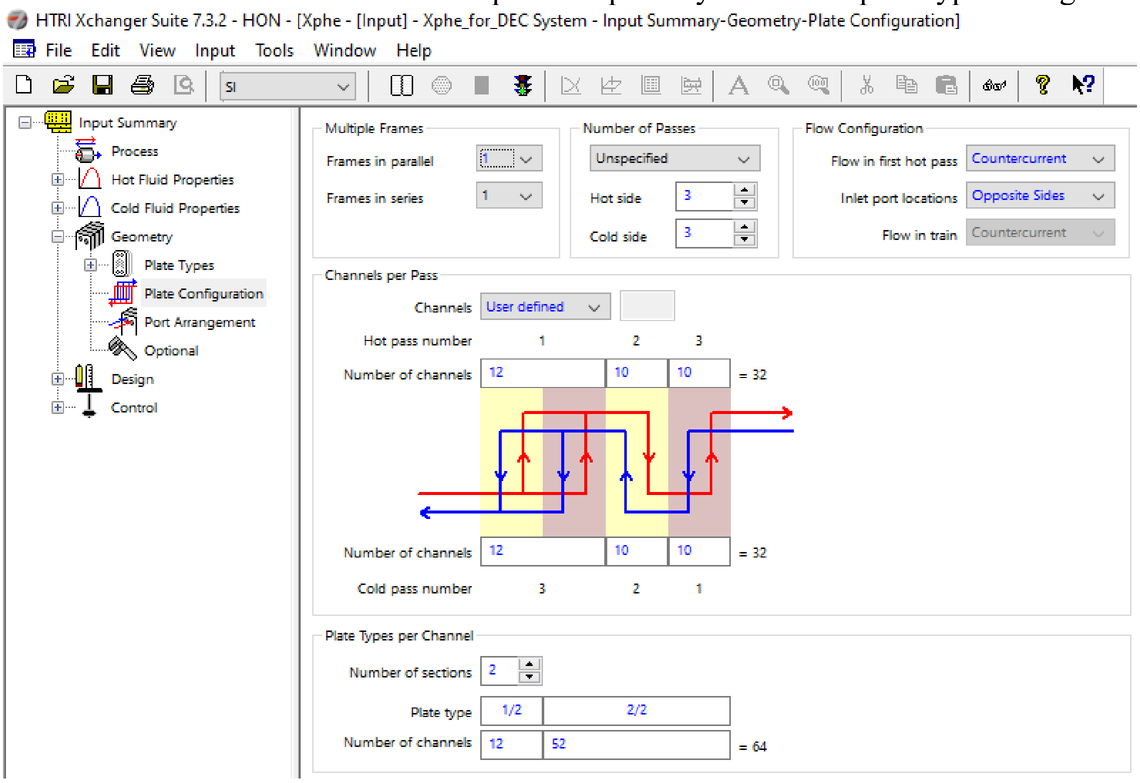

Figure 3. HTRI plate-configuration screen for the 65-plate air-to-air heat-exchanger core.

2.6 Performance indices

The performance comparison used dry-bulb ambient temperature, ambient relative humidity, wet-bulb ambient temperature, cooled-air dry-bulb temperature and cooler efficiency. Cooling efficiency was calculated as the actual dry-bulb temperature reduction divided by the maximum possible reduction between entering dry-bulb and entering wet-bulb temperatures:

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$$\eta = ((T_{db,in} - T_{db,out}) / (T_{db,in} - T_{wb,in})) \times 100\%$$

The mean efficiencies reported in the results are averages of the hourly values in the source tables; they are not recalculated from the averaged temperatures. The exchanger contribution is judged from outlet-temperature stability, mean cooled-air temperature and mean cooling efficiency after the plate core is placed before the direct evaporative pad.

3. Results

3.1 Temperature response of DEC and IDEC

The two configurations behaved differently over the daily record. DEC cooled the air during the earlier hours, but its outlet temperature rose later in the day and reached about 30.35 °C at 20hr00 before falling slightly by 22hr00. IDEC stayed close to 19.2 °C over the same period. The narrow IDEC range indicates that the indirect plate exchanger reduced the sensitivity of the outlet stream to the changing outdoor condition.

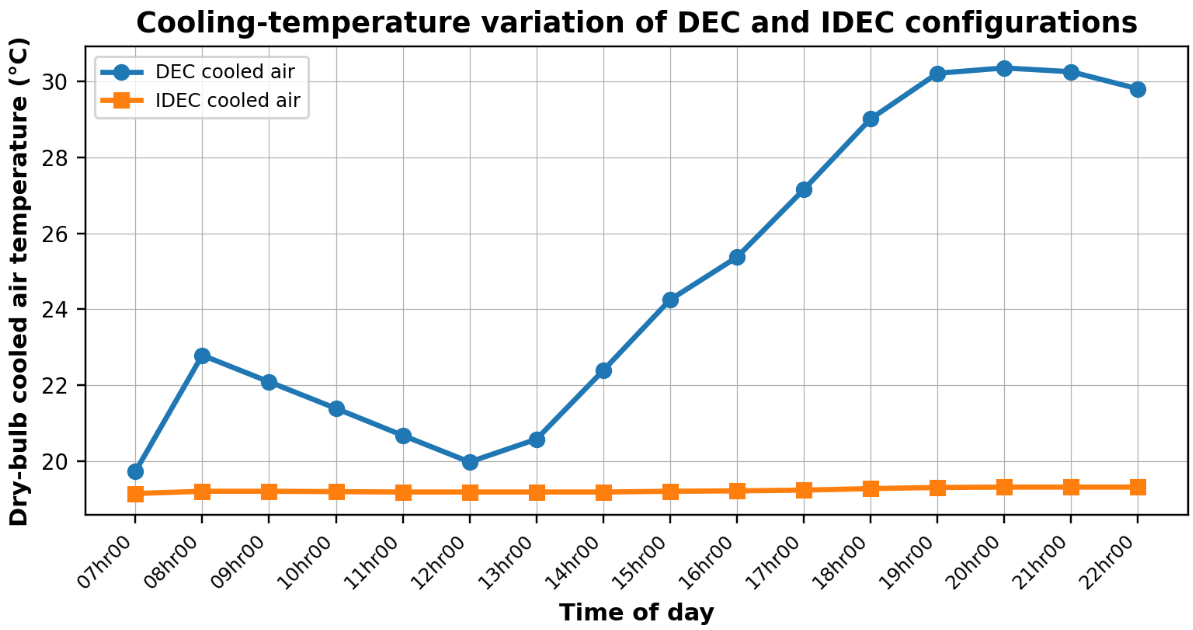

Figure 4. Cooling-temperature variation of DEC and IDEC configurations.

The wider DEC variation reflects its direct dependence on outdoor wet-bulb depression. In the IDEC arrangement, the direct pad received air that had already been sensibly cooled in the plate heat exchanger. This gave a steadier supply condition, which is useful for occupied workshop and institutional spaces.

3.2 Cooling-efficiency comparison

The mean values follow the hourly pattern. DEC produced a mean cooled-air dry-bulb temperature of 24.75 °C and a mean cooling efficiency of 64.05%. IDEC produced a mean cooled-air dry-bulb temperature of 19.23 °C and a mean efficiency of 91.30%. This corresponds to a 5.52 °C lower mean outlet temperature and a 27.25 percentage-point increase in cooling efficiency for the IDEC model.

Table 4. Summary of DEC and IDEC performance values reported in the thesis result tables.

Configuration	Mean ambient DBT (°C)	Mean ambient RH (%)	Mean wet-bulb reference (°C)	Mean cooled-air DBT (°C)	Mean cooling efficiency (%)
DEC	27.25	68.61	23.55	24.75	64.05
IDEC	27.25	68.61	18.51	19.23	91.30

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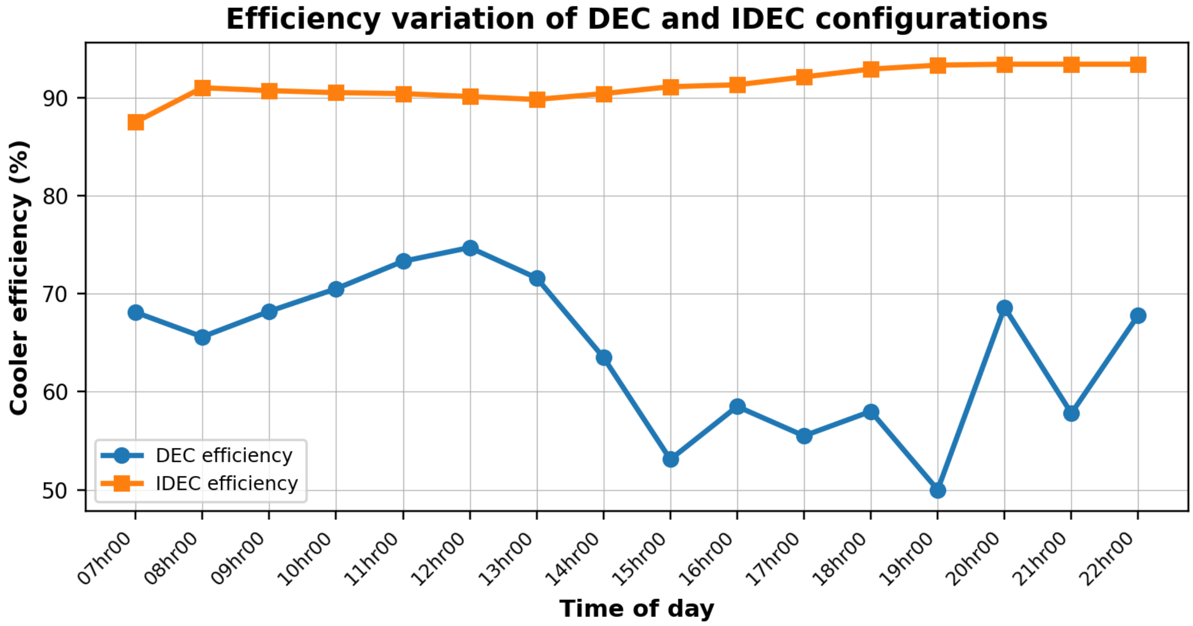

Figure 5. Cooler-efficiency variation of DEC and IDEC configurations.

3.3 Design meaning of the plate heat exchanger

The plate heat exchanger is the main design difference between DEC and IDEC. It removes part of the sensible heat from the primary air before water-contact cooling. In the model result, this pre-cooling stage kept the IDEC outlet close to 19.2 °C while DEC rose with the daily weather sequence. The system-level improvement is therefore linked to the indirect stage, while the exchanger's standalone effectiveness, leakage rate and pressure drop remain prototype test quantities.

Table 5. Plate heat-exchanger design implications from the thesis specification.

Design feature	Engineering implication
65 plates with 32 hot-air and 32 cold-air channels	Provides compact alternating flow passages for sensible exchange.
4.5 mm nominal plate gap	Requires accurate spacers, flat plates and careful sealing during fabrication.
SS304 plate material	Offers durability and cleanability, but fabrication quality controls the final leakage and pressure-drop behaviour.
Countercurrent flow configuration	Supports stronger sensible heat exchange than a poorly arranged flow path.
HTRI pressure inputs	Should be replaced by measured airflow-side pressure-drop data during prototype testing.
Local fabrication risk	Leakage, maldistribution, drainage and fouling must be checked before field deployment.

4. Discussion

The results give a practical design case for a locally fabricable IDEC core. The main engineering gain is the stable IDEC supply temperature. A steady outlet condition reduces the burden on control and helps maintain a more predictable indoor environment for workshops, offices and similar institutional spaces in warm-humid locations.

The plate exchanger is responsible for this difference. In DEC, the wetted pad works directly on ambient air, so performance changes with the outdoor wet-bulb depression. In IDEC, the exchanger first reduces the sensible load of the primary stream. The direct pad then receives cooler inlet air and its outlet condition becomes less variable.

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The specification is a workable starting point for a prototype, but fabrication quality will determine the final performance. A 65-plate SS304 core with narrow gaps can be produced locally only if cutting, spacing and sealing are controlled. Warped plates, uneven spacing, weak edge sealing, poor drainage and fouling can reduce the effective heat-transfer area and increase pressure loss. Fan selection should be based on measured pressure loss from the fabricated core.

5. Limitations and validation needs

The study is numerical and system-level. It uses the TRNSYS and HTRI design values reported by Ozuomba [10]. Prototype validation should measure airflow through both streams, pressure drop across the plate core, fan and pump power, primary and secondary inlet and outlet conditions, leakage between air streams, drainage behaviour, water carry-over and fouling during repeated operation. These measurements provide the basis for comparing prototype behaviour with the model.

6. Conclusion

The 65-plate SS304 air-to-air heat exchanger is a suitable candidate for prototype development in a locally fabricable IDEC system. For the University of Uyo workshop case, IDEC produced a mean cooled-air temperature of 19.23 °C and a mean cooling efficiency of 91.30%, compared with 24.75 °C and 64.05% for DEC. The IDEC outlet temperature also remained much steadier over the daily record. Pressure drop, leakage, flow distribution, heat-transfer effectiveness and cleaning requirements should be measured on the fabricated core before product deployment.

Data availability

The method, heat-exchanger specifications and performance values used in this paper are reported in the cited thesis model and in the tables presented here.

Declaration of competing interest

The author declares no competing interest.

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