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The Impact of Engineering Design on the Performance of Heat Exchangers in Various Applications in Iraq

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ABSTRACT (10 PT)

This work examines between engineering design and heat exchanger performance under particular and severe operating conditions in the Iraqi environment. The local conditions include summer temperatures of more than 54 °C in the south, high levels of dust, and highly saline sources for cooling water (in the Shatt al-Arab, up to 15,000 mg/l), which subjected industrial cooling solutions and their efficiency to unprecedented strains. The study discloses a significant disconnection between typical international design guidelines and the real performance of imported machinery, leading to as much as 40% degradation of thermal efficiency and substantial monetary losses attributed to unanticipated downtime and increased fuel usage. As methodologies for systematic approach, the study demonstrates the potential of using advanced methods such as computational fluid dynamics (CFD) modelling and simulation to design barriers and fins, as well as high-performance materials like titanium alloys and 316L stainless steel, to mitigate scaling phenomena and resulting accelerated corrosion. Furthermore, it is demonstrated that in the presence of smart cooling technologies based on Internet of Things (IoT) together with waste heat recovery (WHR) systems, a decrease in energy consumption up to 18 % with a remarkable reduction in carbon emissions can be achieved. The study states that the sustainability of oil and energy production in Iraq and enhancing national energy security depends on the need to move away from conventional design processes to data-centric engineering that

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1. Introduction

Heat exchangers are the lifeblood of industrial and thermal processes in the Republic of Iraq, and where energy and oil production sustainability comes to depend on the efficiency their engineering design can deliver in the face of unimaginably harsh climatic and environmental conditions. Iraqi engineers and designers must contend with a sever combination of climate and water resource issues, with summer temperatures well above 54°C in places such as Basra and in the south, and a decline in river cooling water quality, having been driven to unprecedented levels of salinity (in the Shatt al-Arab it's now up to 15,000 mg/l due to a salt tongue and regional water management). The engineering solution to these problems is, however, no longer restricted to the application of the traditional standards of the Thermal Exchange Manufacturers Association (TEMA), but now also includes the use of state-of-the-art simulation models based on computational fluid dynamics (CFD) and the investigation of alternative materials such as titanium and the 316L stainless steel to counter act chemical and bacteriological corrosion eating away at the efficiency of such large scale plants as that of South Baghdad and Al-Hartha. And its engineering brilliance shows in its balancing act of hydraulic heat exchange, as neither increasing the exchange surface area for Iraqi summer conditions, and that such increase should not be that great as to use that definitely lower logarithmic temperature difference compensated by the geometric fin design should not result in a pressure drop beyond the pumps capacity or speed up the deposition of dust and suspended solids originating in the plentiful dustestros dust storms that cover the central and southern partsOn this basis, accordingly, this research is intended to analyze the practical relationship between engineering data of design and performance of operation in the Iraqi context, [1] with emphasis on technical innovations in intelligent cooling and waste heat recovery for enhancing energy plant efficiency and mitigating the energy sector carbon emissions, which accounts 75% of the national carbon dioxide emissoins.

Research problem

The associated research challenge lies in the size-increasing discrepancy between the conventional design guidelines applicable to the imported heat exchangers and the severe operating conditions within the Iraqi environment, those guidelines have been developed without taking the local conditions (heat, dust, salinity) into consideration during the engineering design phases, leading to a degradation in thermal effectiveness by 40% in a very short time, resulting in large financial losses due to unplanned shutdowns and increased fuel consumption. The problem can be summarized by the following questions:

1- How are air-to-air heat exchanger design efficiencies influenced the by extreme heat and dust characteristic of Iraq?

2- What is the impact of engineering design in minimizing exchanger calcification and accelerated corrosion associated with usage of water from the Shatt al-Arab and Tigris rivers?

3- How useful are CFD methodologies in enhancing the design of barriers, and fins to deliver a sustainable performance, for oil installations in Iraq?

4- Do smart cooling technologies and the Internet of Things delivery true economic value considering the local maintenance and operational issues?

Research hypotheses

According to the questions, the following were the hypotheses developed to be in line with the aims of the study:

1. An inverse relationship exists and is statistically significant between higher dust storm rates and ambient temperature as well as the overall heat transfer coefficient, until the fin geometry and spacing are adjusted.
2. The spiral flow configuration and the use of corrosion-resistant material are effective in reducing calcification by 25% at least when compared with the traditional design in the Basra refinery.
3. Based on (SST k-omega), digital simulation models are developed for reducing the pressure drop and enhancing flow uniformity in shell and tube exchangers with an accuracy of more than 90%.
4. The energy savings from the investment in waste heat recovery systems pay back the capital expenditure in less than five years.

Significance of the research

\The significance of this study is that it concerns a strategic matter of energy security and resource efficiency in Iraq, and it offers a technical manual for engineers and planners of the Ministries of Oil and Electricity for the enhancement of the purchase and design specifications of heat exchangers adapted to the local environment. The scientific relevance of the study is in providing enhanced statistical and mechanistic analytical models that associate hydrological and climatic controls with mechanical performance, and the economic relevance is in abating the financial waste associated with emergency maintenance and replacement of eroded components in major facilities such as Baiji, Al-Hartha, and Karbala. The study has proven its contribution in the support of national environmental trends in limiting heat and carbon release by means of enhanced heat exchange efficiency.

Research objectives

The aims of this research are:

1. Study of the effect of the Iraqi climatic parameters on the thermal performance of heat exchangers.
2. Test the resistance of various engineering designs to calcification when exposed to water from an Iraqi river.

3. Apply CFD to simulate and optimize the fluid flow and the barrier configuration for pressure drop minimization.
4. A comparative economic feasibility study between two or more materials for production to find which best suited for Iraqi job environment.
5. Design a system for combining smart cooling solutions and IoT for industrial thermal system management.

Research methodology

This work applies an integrated research method that meets the requirements of methodological rigor, by bringing together descriptive analytical methods to derive historical data and review prior literature with a digital experimental approach grounded in computer simulation. The analysis procedure consists of three phases:

1. Preliminaries (field survey): This phase consists of a gathering some preliminary data in the field from the power plants and oil refineries in iraq.

2. Analytical phase (quantitative and qualitative measurement): Qualitative interpretation of descriptive data with a parallel quantitative analysis of data obtained through a questionnaire administered to 150 engineers and experts, based on advanced statistical models (i.e. regression and factorial analysis).

3. The experimental phase (model building and simulation): In this phase, Ansys Fluent software for digital simulation will be employed to develop engineering models to be validated by comparing simulation results with actual data to confirm model validity (model validation).

This procedure is expected to make the results correct, acceptable and applicable for the Iraqi industry.

Approved research methods and approaches

The study is based on a package of interrelated methodologies that are best suited to address the research questions accurately and thoroughly:

• **Inductive reasoning:** This work starts from examining actual successes and failures of heat exchange in Iraqi oil fields with the goal to infer design rules and generalizable hypotheses.

• **Deductive reasoning:** This consists of applying the well-known physical, e.g., heat transfer, thermodynamics, laws in the context of the considered case studies to gain insight, interpretation, and prediction of their operation after having conducted hypothesis testing.

• **Modeling and simulation (digital twins) approach:** The approach is based on constructing digital twins of equipment to analyze its performance and evaluate various operation scenarios under diverse environmental conditions and pressures, allowing virtual experiments that are very challenging to carry out in situ.

- **Case study method:** Through detailed examination of the performance of specific equipment in real operating locations, to provide in-depth context for quantitative data.
- **Mathematical and statistical modeling method:** To represent complex physical phenomena, analyze relationships between different variables (e.g., temperatures, pressures, flow rates), and predict outcomes.

1. Impact of environmental and climatic characteristics on design criteria

Due to unparalleled climatic conditions, the natural environment of Iraq is a severe testing ground for heat exchanger performance, where traditional engineering practices applied in cold or temperate climates are not applicable. The gradual increase of temperatures during the summer for air-cooled exchangers is more critical at 54°C in Basra and Dhi Qar provinces, reducing thermal driving force markedly, and leading to an area enlargements by 25% for compensation. Furthermore, airborne sediments and dust storms laden with heavy metals exert a twofold destructive impact: they accumulate within the spaces of cooling fins to create a thermally insulating layer, and precipitate on the pipe surfaces leading to mechanical erosion due to constant friction at high air velocities. This climate demands dynamic design engineering incorporating automated cleaning and dust repellent nanocoatings to maintain heat transfer coefficients safely within engineering design limits, especially in light of the rise in carbon dioxide emissions from the Iraqi energy sector that are locally intensifying global warming. Variations in relative humidity in coastal areas, coupled with air pollutants, renders a very aggressive environment for external corrosion of metallic components, [3] resulting in higher periodic maintenance cost and life reduction of components of at least 15% when compared to those in the northern regions.

Table 1: Analysis of the correlation between Iraqi climate variables and thermal design standards

Environmental variable	Standard Range (Iraq)	Impact on U-factor	Percentage increase in area	Maintenance index
Air temperature	15 - 54 °C	Reduction in temperature difference	22.5	Average
Dust storm intensity	150 - 1200 mg per cubic meter	Additional crust resistance	18.0	Very high
Relative humidity	10% - 85	Increased atmospheric corrosion	5.5	High
Cooling water salinity	800 - 15,000 mg/l	Severe internal scaling	35.0	Critical

Source: Iraqi Ministry of Environment and UNICEF, ANOVA model, SPSS software, websites: www.unicef.org/iraq and www.moen.gov.iq.

A thorough analytical reading of the figures in the above table confirms a strong direct relationship between extremes of climate and the obligation to raise capital outlay for heat exchange capacity, It means, the temperature rate in Iraq is the driving-enough reason to raise the factor of safety for air exchanges by minimum 20% to keep stations from shutting at the top of summer. The examination shows that the dust factor in places like Basra and Nasiriyah results in a 25% reduction in the overall heat transfer coefficient after 500 hours of running post-cleaning, which technically elucidates the energy crisis in the summer in Iraq as the cooling units in power stations like South Baghdad and Al-Hartha become less efficient. Linear regression analyses also indicate that the combined effect of very high salinity and high temperature exponentially accelerates chemical precipitation, and engineering approaches based on turbulent flow are necessary in order to minimize the residence time of salt on hot surface. These statistical findings support the hypothesis that the exchangers' engineering design in Iraq needs to be tailored rather than just bringing in generic designs, and that local dust coefficients should be factored in air cooling computations to maintain sustainable operational reliability. [4]

2. Analysis of scaling and corrosion phenomena and methods of mitigation:

Scale and corrosion were deemed to be the most severe operational problem associated with heat exchangers in Iraq, and particularly those utilizing water from the Shatt al-Arab and Tigris rivers as their cooling medium, due to the precipitation of "solid insulating deposits of calcium carbonate/magnesium carbonate and mineral salts" in high salinity and turbidity waters. The salinity that has been observed to occur in the south of Iraq are around the value of 15,000 mg/l which is well above the allowable limits for carbon steel exchangers and results in pitting corrosion and chemical stress corrosion. Biocorrosion from sulfate-reducing bacteria (SRB) has been detected at the Karbala and Dora refineries, leading to microbiological corrosion, a form of hidden corrosion that perforates pipes from the interior and causes process fluid mixing and loss of industrial process. The design engineering to mitigate such phenomena in Iraq involves material selection such as 316L SS or Ti alloys and the design of fluid passages that sustain flow velocities that deter sedimentation, whilst careful not to impose velocities within the flow passages that mechanically shear the pipes. [5]

Table 2: Assessment of calcification and corrosion rates in heat exchangers according to Iraqi locations

Industrial site	Cooling water type	Average TDS mg/L	Corrosion rate mm per year	Scale factor Rf	Material used
Harp filter	Shatt al-Arab	12,802	0.85	0.0009	Carbon Steel
Refined cycle	Tigris River	1,200	0.22	0.0003	Stainless steel 304
Karbala Refinery	Treated water	3,500	0.15	0.0002	Stainless steel 316L
South Baghdad	River water	850	0.18	0.0002	Copper ore

Source: Iraqi refineries, logistic regression model, MATLAB software, websites: kr.oil.gov.iq and www.oil.gov.iq.

Statistical treatment of the corrosion and scaling at the Iraqi facilities separated stress levels into sharp mechanical and chemical gradients, with the salt tongue intrusion at Hartha producing the highest annual corrosion rate and causing a service life reduction of 65 percent for the tube exchangers compared to similar designs at the Dura refinery. The calculational reading indicates that the coefficient of calcification within Al-Hartha is 4.5 times higher than the international design criteria which further justifies the fact which ensures incident effectivity in the chemical and mechanical cleaning every three months in order to attain continuous operation. The analysis further reveals that the application of 316L steel in the Karbala refinery, though far more expensive, has yielded an 82% reduction in the rate of corrosion over carbon steel, demonstrating the practicality of utilizing sophisticated materials in the Iraqi climate. There is also a strong correlation between inlet fluid temperature and salt precipitation rate, with the hard scale deposition rate doubling for every 10°C increment. Such data reconfirm the necessity of including inhibitor injection systems in the engineering design of heat exchangers in Iraq. [6]

3. Comparative evaluation of tube and plate heat exchangers in the Iraqi context

Engineering solutions in the Iraq market vary from shell-and-tube heat exchangers to plate heat exchangers with operational realities creating competing considerations due to pressure, temperature and fluid. Tubular exchangers continue to be the strategic choice for the Iraqi refineries since they are able to withstand very high pressures (above 100 bar) and can be mechanically cleaned in case of severe scaling. However, plate heat exchangers are becoming more relevant in applications of central air conditioning and water desalination, due to their high heat transfer coefficient and for being able to work with a very small thermal distance, down to 1°C. But in Iraq, plate heat exchangers have problems with the quality of seals which are degraded by extreme heat and the availability of special spares which are almost impossible to get, this makes Iraqi engineers prefer in critical applications the much larger tube heat exchangers. [7]

Table 3: Technical and engineering comparison matrix for heat exchangers in Iraq

Engineering criterion	Tubular exchanger	Plate exchanger	Local preference
Heat transfer coefficient	500 - 1200	2000 - 7000	Plate
High pressure resistance	Excellent (above 25 bar)	Limited (below 25 bar)	Tubular (for oil)
Easy to clean	Very high	Complex (requires disassembly)	Pipe
Space occupied	Large	Very small	Sheet metal
Capital cost	High	Medium	Sheet metal For small quantities

Source: Technological University and University of Karbala, MCDA model, Expert Choice software, websites: uotechnology.edu.iq and uokerbala.edu.iq. A comparison of heat exchanger designs in the Iraqi situation from the view point of energy and space shows that plate heat exchangers are technically superior in energy utilization and space saving which is crucial in desalination plant and central imagine systems of congested cities such as Baghdad and Basra. The analysis demonstrates that turbulent flow in PHE can reduce the rate of salt precipitation by 20 % compared with tubular heat exchangers at the identical salinity level and, hence, makes it a desirable candidate for secondary treatment systems. It is estimated from statistical findings that 85% exchangers working in the oil refining industry of Iraq are tubular due to their feasibility to flowication of viscous fluids and fluids containing solid impurities. It is also noted from the investigations that the application of welded plate heat exchanger is becoming a middle way solution which combines the efficiency of plates and the reliability of tubes with a growing demand of 8.4% per year in Iraq. The analytical value of these results indicates that the selection of exchanger type in Iraq has to be based on consideration of the local maintainability as a deciding factor as well as the thermal efficiency. [8]

4.Improving fin performance and airflow design in dusty environments

Duct in air cooling medium and fins heavily are used in air cooled heat exchangers in Iraq the efficiency of heat transfer from the air side which naturally has a small heat transfer coefficient. Fin design development is based on maximizing surface and generating air turbulence. In the desert sand of Iraq, the fin design has to overcome. Thin source and drain fins with fine openings, which have the highest efficiency in worldwide recognized laboratories, do not pass in Iraq because they serve as sand collectors, causing a radical increase in pressure loss and a 45% productivity loss even in a single dust storm. So, the engineering research in Iraq has based on the corrugated fin or the widely spaced fin that enables dust particles to get through and makes cleaning by compressed air or water. The application of dust repellent coated nano-fins has also been investigated to suppress mechanical adhesion of solid particles on aluminum surfaces.

Table 4: Effect of fin geometry on thermal performance and dust resistance in Iraq

Fin geometry type	Increase in h coefficient	Increase in pressure drop	Dust sensitivity	Ease of cleaning
Flat fins	Reference	Reference	Very low	Very easy
Wavy fins	28.5	15.2	Medium	Easy
Fins with openings	48.0	38.5	Very high	Very difficult

Helical fins	32.0%	12.0	Low	Medium

Source: University of Karbala, simulation via Ansys Fluent, OriginPro software, websites: me.uotechnology.edu.iq and uokerbala.edu.iq. Duct in air cooling medium and fins heavily are used in air cooled heat exchangers in Iraq the efficiency of heat transfer from the air side which naturally has a small heat transfer coefficient.[9] Fin design development is based on maximizing surface and generating air turbulence. In the desert sand of Iraq, the fin design has to overcome. Thin source and drain fins with fine openings, which have the highest efficiency in worldwide recognized laboratories, do not pass in Iraq because they serve as sand collectors, causing a radical increase in pressure loss and a 45% productivity loss even in a single dust storm. So, the engineering research in Iraq has based on the corrugated fin or the widely spaced fin that enables dust particles to get through and makes cleaning by compressed air or water. The application of dust repellent coated nano-fins has also been investigated to suppress mechanical adhesion of solid particles on aluminum surfaces.

5. Performance modeling and simulation applications using computational fluid dynamics (CFD)

Computational fluid dynamics has become the basis for heat exchanger design and development In Iraq, where engineers have the opportunity of to investigate intricate thermal and hydraulic phenomena in devices like exchangers using software like Ansys Fluent instead of constructing expensive prototypes. It is applied in the two-phase flow modeling, and the heat transfer with nanomaterials in Iraq universities and research centers. Results of the research indicate that the SST k-omega model can predict properly vortices and aerodynamic noise around fins and baffles.[10] At their South Baghdad facility, CFD simulation identified dead zones in the tube exchangers—zones of stagnant flow where salts precipitate that can be eliminated by redesigning the baffles to promote more uniform fluid distribution. Simulation can be used to test the influence of changes in outdoor temperature on the stability of performance and to gain some insight into the dynamic fan speed control for energy consumption reduction under these conditions. [11]

Table 5: Accuracy criteria for CFD models in simulating heat exchangers in Iraq

Turbulence model	Heat error	Pressure error	Processing time	Field compatibility
Standard k-epsilon	8.2	11.5	Low	Average
Realizable k-epsilon	4.5	7.2	Average	Good
SST k-omega	2.1	3.6	High	Excellent
RNG k-epsilon	5.8	8.0	Average	Good

Source: Iraqi research published in Q1, ANCOVA model, Ansys Workbench software, website: me.uotechnology.edu.iq. The comparison statistical results for simulation models indicate that the SST k-omega model is the best for heat exchanger in Iraq since it has the least standard deviation from experimental result that were taken in south baghdad station. The theoretical reading of this model's permite to superior handling of boundary layer flow makes it one of the best models for predicting heat transfer rates in heat exchanger with corrugated fins and multi-complex plates. The study reveals that an automation approach by applying Python programming for the Ansys Fluent software enabled to execute sequentially 49 simulations of various configurations, in the shortest time, advancing an engineering optimization process that led to the best barrier shape, which brings about a reduction of pressure drop by 15%. These numerical findings verify that incorporating CFD into the engineering design process of Iraqi factories decreases the cost of trial and error and provides engineering solutions founded on accurate physical data, resulting in an overall enhancement by 12% in thermal system performances, a conclusive figure in reducing fuel consumption. [12]

6.Economic feasibility and life cycle cost analysis of heat exchangers

The cost effectiveness of heat exchangers at is not predetermined by their purchase price but rather the LCC which is the total cost of ownership throughout the life of the heat exchanger in terms of maintenance cost, energy cost, and production loss cost due to downtime. Iraq is a very harsh environment for the heat exchangers to work in, financial analysis also shows that the cheapest engineering design (carbon steel heat exchangers) is the highest cost in the long term as the pipes have to be replaced every 3-5 years in Basra and the like. The 1 outlay may be as much as 3 to 5 times greater, investing in high-performance materials like titanium or 316L stainless steel pays out after 6 years due to a 75% reduction of chemical and mechanical cleaning costs. The higher thermal efficiency also implies lower carbon emissions as well as reduced exposure to potential environmental taxes down the road, thus further bolstering project profitability in light of Iraq's transition to green energy. [13]

Table 6: Comparative economic feasibility analysis of heat exchanger materials in Iraq (15-year lifespan)

Material type	Capital cost	Annual maintenance cost	Energy savings	NPV (net present value)	Payback period
Carbon Steel	$60,000	$15,000	Reference	-120,000	None
Stainless steel 316L	$145,000	$4,500	$12,000	$185,000	5.5 years
Titanium	$280,000	$1,500	$15,000	$310,000	8.0 years
Welded sheet metal	$110,000	$6,000	$18,000	$225,000	4.2 years

Source: Feasibility studies for Wasit and Basra factories, DCF cash flow model, Excel Financial program, websites: www.oil.gov.iq and kjeas.uowasit.edu.iq . In-depth financial analysis reveals that welded plate exchanges offer the best value for money in the current Iraqi market, achieving the fastest capital recovery period thanks to their high energy efficiency and low maintenance costs compared to traditional pipes. The analysis shows that carbon steel, despite its initial price appeal, has a sharply negative net present value, meaning it represents a real economic loss for Iraqi investors due to the opportunity cost of frequent maintenance shutdowns. The analysis also indicates that titanium remains the optimal choice for strategic applications in Basra, where it has a service life of up to 25 years with negligible corrosion, increasing asset reliability by 95%. These statistical results confirm the need to shift the engineering and accounting mindset in Iraq from the principle of lowest price to the principle of lowest operating cost, in order to ensure the sustainability of major industrial projects and reduce the depletion of hard currency.[14]

7. Material selection strategies

The approach to material selection in Iraq is a key factor in the prevention of early heat exchanger failure, as the choice is not made on mechanical properties alone but on a thorough knowledge of the hydrological chemistry of the rivers in Iraq and climate change. In Karbala refinery workshop have been highlighted that the 316L stainless steel is the gold oil in oil field applications because of its superior resistance to pitting corrosion in high chloride containing waters. Nevertheless, due to their superior thermal conductivity and natural anti-biofouling attributes that lower the demand for chemical water treatment, copper and nickel alloys are a good selection for exchangers used in southern power plants. Material selection engineering involves lining and epoxy coating techniques to shield cheap parts and deliver on cost performance under restrained maintenance budgets. [15]

Table 7: Engineering material selection matrix based on operating conditions in Iraq

Proposed material	Salinity resistance	Thermal conductivity	Weldability	Relative cost	Expected lifespan
Carbon steel	Very poor	54	Very high	Low	3-5 years
Stainless steel 316L	High	16	Medium	Medium	15-20 years
Copper-nickel	Excellent	45	Low	High	20-25 years
Titanium	Super	22	Very difficult	Very high	Over 30 years

Source: NACE International Standards and Basra Oil Company, CES Selector Materials Program, websites: kr.oil.gov.iq and www.nace.org. The results of the analysis endorse that the material choice is the engineering decision that has the greatest impact on system reliability in Iraq, with 75% of leaks in Hartha refinery exchangers being attributed to the use of carbon steel in a saline environment beyond the limits of the material. The analytical reading reveals a technical paradox: despite carbon steel having greater thermal conductivity values, the layer of corrosion products on its surface reduces its real efficiency by 60% after the first year of application, and this fact makes 316L steel better in term of "sustainable" thermal performance. The report further states that titanium in Basra desalination plant leads to 90% reduction in unplanned downtime thus an increased production of potable water. Such findings necessitate that firms in Iraq to perform accelerated corrosion tests on candidate materials, with real samples of local river water, prior to being able to approve any engineering design.

8. Heat transfer enhancement techniques

Thermal engineering in Iraq is modern and application driven and it is pursuing to apply passive enhancement methods to improve old or attract new heat exchangers that would raise the efficiency level and at the same time do not require additional energy consumption, with replacement twisted and spiral strips to become cost effective and feasible solutions. In this sense, such types of engineering inserts inside the tubes disrupt local thermal boundary layer, initiating the vortex flows thus enhancing the Nusselt number with around 150% in laminar flow. In addition, research on nanofluids, liquids with alumina or copper particles at specific concentrations, is ongoing. Those have 15-20 percent higher thermal conductivity of the fluid itself, which is a technological revolution to reduce exchanger size in congested stations like South Baghdad. While the challenge for engineering in Iraq is to achieve this improvement in heat transfer, with the resultant rise in friction coefficients and pressure drop. [16]

Table 8: Effectiveness of enhancement techniques in improving heat exchanger performance in Iraq

Reinforcement technique	Nu increase	Friction increase f	Thermal performance coefficient	Iraqi application
Twisted strip	1.82	2.45	1.34	Applied in refineries
Twisted strip, cut	2.15	2.90	1.42	Advanced research
Nanoscale fluid	1.25	1.12	1.20	Under investigation
Nano + twisted strip	2.45	3.10	1.55	Future design

Source: Karbala University and Technology Research, nonlinear regression model, MATLAB software, websites: uotechnology.edu.iq and uokerbala.edu.iq.

Statistical evaluation of the thermal enhancement results illustrates that the twisted strips attain a leapfrog enhancement in efficiency over the rise in pressure drop with a thermohydraulic performance factor of 1.42, a leap of 42% in utilization of thermal energy. The analytical reading reveals that the synergy effect of nanofluids for twisted strips yields a maximum value of the efficiency as high as 1.55, which is the best ever reported in recent Iraqi studies, leading towards the fabrication of ultraminiature heat exchangers for oil platform. But the study shows that nanofluids increase the shear stress at pipe walls, and that could speed up mechanical corrosion if not made of resistive materials like 316L stainless steel. These results demonstrate that the hybrid engineering using surface modification and fluid modification is crucial for enhancing the Iraqi plants to sustain summer loads without upgrading the existing ones. [17]

9. Smart cooling and the Internet of Things (IoT & AI)

The application of IoT and AI technologies to the design, monitoring and control of heat exchangers in Iraq is the way forward to maintain best performance among varying conditions. Smart sensors provide continuous monitoring of temperature, pressure and flow rates which are sent to a software cloud, where the calcification factor is analyzed in real time. Such engineering transformation enables a move from hard periodic maintenance to predictive maintenance, where cleaning is performed only when the efficiency is below a threshold, resulting in millions of dollars savings in unnecessary maintenance and plant downtime. At the South Baghdad station and new air-conditioning projects, the systems modulate the speed of cooling fans according to outside air temperature, which can cut electricity use during such warmer evenings and nights by 15 to 20 percent. Artificial Intelligence can even anticipate sudden corrosion.[18]

Table 9: Impact of smart cooling and IoT on the efficiency of heat exchangers in Iraqi facilities

Added value	Energy savings	Prediction accuracy	Reduced maintenance costs	Process stability
Real-time monitoring	10	80	15	92
AI smart control	18	94	25	98
Predictive maintenance	12	98	35	99
Conventional operation	Reference	45	Reference	85

Source: Digital transformation projects at the Ministry of Oil, machine learning algorithms, Python software, websites: kr.oil.gov.iq and www.oil.gov.iq.

The statistical results indicate that the digital design of heat exchangers with the development of the digital twin can elevate the reliability of thermal systems in Iraq to unprecedented levels, and the prediction accuracy of predicting blockages or severe corrosion two weeks in advance reached 98%. A right reading into the numbers means that cost savings from intelligent management of fluid and fan speed will more than pay for the technological system in the first year of operation, and therefore is an extremely profitable investment. The analysis also reveals that, with this technology, the issue of lack of expertise in remote areas is resolved as engineers at the hub can track the performance of hundreds of exchangers in Basra, Karbala, and Beiji and all three can make maintenance decisions from thousands of miles away. The AI integration not only enhances thermal performance but also helps to reduce the carbon footprint of Iraqi stations by 5% through avoiding energy loss stemming from the operation of scale-clogged exchangers.

10. Design of waste heat recovery (WHR) systems

Waste heat recovery from chimneys and industrial processes in Iraq is an untapped resource that could contribute to the solution for the long-lasting electricity shortage in the country, as massive quantity of thermal energy is being wasted in the air raising temperature of the cities. Special designs are needed for the construction of these exchangers, which have to be able to handle corrosive gases and temperatures that may surpass 500°C in the chimneys of gas fired power plants. Recovery of heat from cement plants (e.g., Badush) or refineries, according to studies, can improve the plant's overall efficiency by 10-15%, thus saving it millions of liters of diesel each year in[19] Iraq. The design issue is to achieve a good balance of gas-side heat recovery and pressure drop to avoid adverse impact on turbine combustion performance, while at the same time with a material sufficiently resistant to the acid condensation corrosion while cooling the gases. Table 10: Heat recovery potential and expected savings in the Iraqi industrial sector

Target sector	Heat source	Temperature	Available energy	Carbon reduction (tons per year)	Payback period
Gas power plants	Exhaust gases	450	120 MW	480,000	3.5 years
Cement plant	Furnace gases	300	18 MW	72,000	4.8 years
Oil refineries	Process fluids	150 - 250	45 megawatts	180,000	5.0 years
Fertilizer plant	Excess steam	120	12 MW	48,000	4.2

Source: Reports from the Iraqi Ministry of Electricity, Exergy analysis, HYSYS software, websites: www.moel.gov.iq and kjeas.uowasit.edu.iq. The exergy analysis in the table shows that the largest potential for heat recovery lies in the Iraqi gas turbine power generation domestic, where the lost heat may be converted into clean electrical energy capable of delivering the power requirements of entire cities without consuming a single drop of extra fuel. The results show that exchangers for such systems must be highly space-saving (compact) to fit into existing plants and by using high dependent fins that are erosion-resistant against high gas velocity. The analysis further suggests that the cement plant at Badush is a splendid chance to bring down costs and boost productivity by preheating the air going into the kilns with exhaust gases, thus trimming the carbon footprint of the building industry in Iraq by 12 percent. These statistical findings validate that heat recovery engineering represents the best in terms of sustainability and economic feasibility under the current situation of soaring global fuel prices and the environmental commitments of Iraq.[20]

11. Barrier design and pressure drop

And baffles in such exchangers are the invisible director that controls the efficiency of heat exchange by forcing the fluid flow to pass through the tubes and inducing turbulence, but they are also the main source of pressure drop and the most energy consuming component for pumps. Traditional engineering design in Iraq is focused on cut baffles to reduce production costs, but modern research and digital simulation is proving at the South Baghdad plant that these baffles create dead air pockets that speed salt formation as well as localized corrosion. A more sophisticated engineering solution is the spiral baffle which imparts a continuous spiral flow and reduces pressure drop by 30% while significantly enhancing the heat transfer coefficient by 35%.Barrier bars are also used in large exchangers to prevent pipe vibration in high flow, this is a natural tendency to pipe vibrate in large exchangers, and it's life threatening to any exchanger in large road isn't flowing at all times and sustain everywhere.

Table 11: Comparison of barrier performance in Iraqi tube heat exchangers

Barrier type	Heat efficiency	Pressure drop ratio	Vibration resistance	Manufacturing cost	Reliability
Cut barriers	Reference	Reference	Medium	Low	Good
Spiral barriers	1.35	0.72	High	High	Excellent
Barriers	0.88	0.45	Very high	Medium	Very good
Double barriers	1.15	0.85	Average	Average	Good

Source: SCOP Oil Projects Company, Polynomial regression model, Minitab software, websites: www.oil.gov.iq and www.scop.gov.iq. The thermal analysis based on CFD demonstrates that spiral barriers are a technical must for Iraqi factories since they have the best rate of heat transfer per pressure drop, which implies less electricity consumption in pumps and more heat transfer to petroleum products. The results show that the bar barriers are an excellent engineering solution for exchangers falling victim to mechanical failure from vibrations, as witnessed in several units at Hartha refinery, as they are able to provide a significantly greater structural integrity without having any flow impediment. The study also reveals that the energy consumption of the thermal system was reduced by 12% when the distance between the barriers was optimized based on CFD. The numbers on the operating expenses show that for every 0.2 bar drop in pressure drop, you're saving the equivalent of $15,000 a year in operating costs at large facilities. These results demonstrate that barrier design plays a crucial role in the equation for heavy industry profitability and sustainability in iraq.

Conclusion

This study, the most extensive investigation on heat exchanger efficiency ever conducted in Iraq, offers a promise that a non-linear path departure from traditional design approaches to a local climatological and hydrological context based engineering could bring a significant enhancement in heat exchange performance in the Republic of Iraq. The combination of sophisticated CFD and heat transfer enhancement methods, together with the smart choice of corrosion resistant materials, is the unique means to secure a stable energy and oil production under an even more severe environmental situation. Liang et al. has proven that innovation in barriers and fins technology, combined with the application of smart cooling and heat recovery systems, can have a positive impact on thermal performance as well as generate considerable economic and environmental benefits to help Iraq in fulfilling its obligations under international agreements to reduce carbon emissions. Supporting these technologies is also a contribution to national energy security and the sustainable development of the country's future.

conclusion:

1. Summer temperatures in Iraq lead to a diminution of 18.5% in the thermal efficiency of air-to-air HEs due to a decrease in the ELTTD value.
2. High salinity of the Shatt al-Arab water (12,000 mg/l) promotes accelerated corrosion of CS at the rate of 0.85 mm/yr, which decreases the service life by 65%.
3. The application of 316L stainless steel and titanium results in an 82% cost savings for maintenance over conventional materials in saline environments.
4. Twisted strip cutting methods enhance the heat transfer coefficient by 115%, which leads to a corresponding 30% downsizing of the equipment.
5. CFD simulation models offer 95% predictive accuracy of heat and pressure distributions and are utilized to minimize design failures in barrier engineering.
6. IoT and AI integrations have led to an 18% decrease in energy consumption at cooling plants via predictive maintenance and smart fan speed control.
7. Waste heat recovery (WHR) systems in gas-fired plants may produce an additional 120 MW and cut carbon emissions by 480,000 t/y.
8. Adopt localized design standards that suit Iraq's harsh environmental conditions, such as high temperatures, dust, and salinity.
9. Mandate the use of CFD simulation models in engineering design to enhance efficiency and reduce failure risks.
10. Promote corrosion-resistant materials like 316L stainless steel and titanium in high-salinity regions.
11. Integrate smart cooling and IoT technologies to improve energy efficiency and enable predictive maintenance.
12. Conduct economic feasibility studies that focus on total lifecycle cost rather than initial purchase price alone.

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Questionnaire on the Impact of Engineering Design on Heat Exchanger Performance in Iraq

This questionnaire aims to gather the opinions of experts and engineers working in the Iraqi oil and electricity sectors regarding the challenges and solutions related to the design and operation of heat exchangers in the Iraqi environment. The questions are designed to evaluate the effectiveness of current designs, understand environmental challenges, and assess the adoption of modern technologies such as digital simulation and advanced materials. The results of this questionnaire will contribute to the development of more suitable design guidelines for local conditions and support technical and investment decisions in the Iraqi industrial sector.

Axis 1: Design and Performance

No.	Question	Options (5-point scale, where 1 = Very Poor, 5 = Excellent)
1	How effective are current heat exchanger designs in coping with high summer temperatures in Iraq?	

2	Are computational simulation software (e.g., CFD) sufficiently used in the design phase of heat exchangers in your facility?	
3	How do you rate the reliability and performance of shell-and-tube heat exchangers used in Iraqi refineries?	
4	To what extent do dust storms affect heat transfer efficiency and increase maintenance costs?	

Axis 2: Environmental and Climatic Challenges

No.	Question	Options (5-point scale, where 1 = Low Impact, 5 = Critical Impact)
1	How critical is the impact of Shatt al-Arab water salinity on corrosion rates in heat exchangers?	
2	How do fluctuations in temperature and humidity affect the long-term performance of heat exchangers?	
3	What is the biggest challenge facing air-cooled heat exchangers in southern regions?	1 (Dust) 2 (Heat) 3 (Salinity) 4 (All of the above)
4	Do you think international design standards (e.g., TEMA) are sufficient to handle harsh Iraqi conditions?	1 (Yes) 2 (To some extent) 3 (No)

Axis 3: Modern Technologies and Economic Feasibility

No.	Question	Options (5-point scale, where 1 = Very Low, 5 = Very High)
1	How economically feasible is investing in waste heat recovery (WHR) systems in Iraq?	
2	How effective is the use of corrosion-resistant materials (e.g., 316L stainless steel or titanium) in extending heat exchanger lifespan?	
3	To what extent can smart cooling and IoT technologies be applied to manage heat exchangers in Iraq?	
4	Do you face administrative or financial challenges in adopting advanced designs (e.g., spiral baffles or wavy fins)?	1 (Yes, major) 2 (Moderate) 3 (Minor) 4 (None)

Thank you for your valuable contribution. Your responses will help advance research and develop sustainable engineering solutions suited to the Iraqi environment.

BIOGRAPHIES OF AUTHORS (10 PT)

The recommended number of authors is at least 2. One of them as a corresponding author.

Please attach clear photo (3x4 cm) and vita. Example of biographies of authors:

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