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Research Article

Design and Thermal Performance Analysis of an Operating Table-Integrated Heating System for Perioperative Hypothermia Management

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Keywords

Patient safety,
Perioperative warming,
Embedded heat exchanger,
Conductive patient warming.

Abstract

Low body temperature during surgery continues to be a common medical issue, often tied to poor blood clotting and slower tissue recovery. Instead of using conventional forced-air devices, this research examines a heat delivery method integrated into the surgical bed itself. A controlled system was created, circulating warm water through pathways inside the table surface to preserve normal body temperature without disturbing airflow patterns around the procedure area. Wooden models were shaped to test two different internal layouts: one followed a classic spiral pattern (Plate 1), while the other used an irregular, branching route (Plate 2). Trials covered flow conditions from 4000 to 25000 Reynolds numbers, applying input heat ranging from 42 to 50 °C. Results indicated Plate 2 surpassed the conventional model, delivering an 18% higher mean Nusselt number under maximum flow. Despite fluctuations, thermal scans revealed consistent performance - surface temperatures varied only ±0.4°C on average. Throughout trials, readings stayed safely between 37 and 40°C, meeting required medical thresholds. Behind the improvement: carefully shaped channels likely trigger swirling motions that boost heat exchange. Rather than relying solely on external power, built-in conduction pathways offer a simpler path toward effective patient warming.

1. Introduction

Body temperature sits between 36°C and 37°C when metabolic functions run smoothly. Though internal sensors track heat shifts, the brain's hypothalamus manages adjustments using signals from skin and deeper structures. Tight control happens because small deviations disrupt cellular activity. While warmth regulation feels automatic, it relies on constant feedback loops running below awareness. Under standard physiological conditions, the body's thermoregulatory center is highly sensitive, triggering corrective mechanisms in response to core temperature deviations as minor as 0.2°C [1,2]. Hypothermia that develops during the surgical process can lead to negative consequences such as infection, bleeding, cardiovascular complications and loss of comfort in patients. Operating table-based heating systems are among the active body surface heating methods and are widely used to prevent hypothermia [3].

Anaesthetic drugs administered during surgical interventions suppress hypothalamic functions and increase the response threshold of the central thermoregulation system. This causes a delay in the physiological response to changes in body temperature, and the thermoregulation system becomes activated only at deviations of 4°C [4,5]. As a result, heat loss increases rapidly and the risk of perioperative hypothermia increases. Perioperative hypothermia is not only related to the effect of anaesthetic drugs, but also to many factors such as the ambient temperature of the operating room, the temperature of intravenous fluids, the type and duration of the surgical intervention, the age, gender and body composition of the patient [6,7]. In the literature, it has been reported that unwanted hypothermia develops in approximately 50% of surgical patients, and the body temperature drops below 36°C in half of these patients within the first hour and in one fifth of these patients by the second hour[8]. This is associated with significant clinical complications such as increased surgical wound infections, increased blood loss due to coagulation disorders, slowed metabolism of the drugs used, and prolonged postoperative recovery [6,9,10]. Therefore, maintaining thermal balance throughout the surgical process is a critical parameter that should be managed with a multidisciplinary approach. In the literature, hypothermia is reported to be associated with adverse clinical outcomes such as cardiovascular stress, increased bleeding risk, delayed wound healing, increased infection rates, and prolonged hospital stay [5,11]. Therefore, maintaining normothermia during the operation has become an essential element of patient care.

One of the most common methods to prevent hypothermia is forced air warming systems (FAW). These systems provide convective heat transfer by directing heated air to the patient [12]. However, some studies suggest that these systems may contaminate the sterile surgical field by disrupting laminar airflow, potentially increasing the risk of surgical site infection [13–15]. In addition, punctures and tears that may occur on them during surgery reduce the efficiency of the devices and question the safety of use. Alternatively developed electric heating pads and circulating hot water pads can provide more homogeneous heating than FAW systems as they provide heat transfer by direct contact [16]. However, these systems also have limitations such as high cost, sterilisation difficulties and limited usage area [7,17]. In addition, since most of these devices are placed on the patient or positioned around the operating table, they can limit the placement of surgical equipment and the mobility of personnel. A decrease in body temperature below 28 °C leads to serious cardiovascular complications (hypotension, bradycardia,

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arrhythmia) and increases the risk of mortality [5]. Therefore, various thermal protection strategies are applied preoperatively, intraoperatively and postoperatively to prevent hypothermia. These methods are generally classified as passive insulation systems and active heating systems.

Passive insulation is provided by thermal blankets, surgical drapes, woollen textiles or plastic materials with metal additives and can prevent heat loss to a limited extent [18]. However, especially in emergencies such as traffic accidents, the risk of hypothermia increases due to insufficient response time, and the use of active heating systems is recommended in such cases [19]. Active heating systems include blankets with forced hot air blowing, convective heating devices, radiant heaters and intravenous liquid heaters. These systems, which provide heat transfer by convection, are more effective in preventing central heat loss [20]. In a randomised study conducted by Bennett et al. (1994)[20] with 45 patients undergoing hip surgery, body temperature remained constant only in the active heating group. Similarly, in the large-sample study of Lupo et al. (2020) [21], forced air heating systems were reported to reduce the risk of hypothermia more effectively than polymer blankets. Monteiro et al. (2018)[22] showed that upper body warmers are more efficient than lower body warmers in closed aortic surgeries. In addition, Brodshaug et al. (2019)[23] stated that forced air heating provides a return to normothermia in a shorter time than passive insulation. Although heated intravenous fluid application alone is not sufficient, it gives effective results when combined with other heating systems. Smith et al. (1998)[24] reported that patients given fluid heated to 42 °C had higher body temperature compared to those given fluid at room temperature. As an emerging method, negative pressure heating systems locally heat extremities and limit environmental heat loss [5].

In recent years, studies on new generation heating systems that can be integrated with the operating table have intensified in order to eliminate these problems. These systems provide both a more controlled maintenance of the patient's body temperature through closed-circuit heating elements embedded in the operating table top or circulating hot water pipe systems and ease of use without disturbing the surgical field layout [25]. In addition, conduction-based heat transfer through direct contact offers a more stable and safe heating profile compared to convective systems [14]. In this context, in our study, a base heating system integrated with the operating table, providing hot water circulation through pipes embedded in the duct system, was designed and experimentally evaluated for performance. Unlike the existing systems, it has been analyzed that this prototype will have both a protective effect against hypothermia and positive contributions to the comfort and range of motion of the operating room personnel.

A fresh approach defines this study - using a sealed, electrically conductive heater built into the operating table itself. Instead of relying on outside airflow, warmth moves through carefully arranged materials. Because of this setup, clean air overhead stays undisturbed, avoiding the messiness common with older warming systems. Built right into the structure, the system removes bulky parts hanging nearby. With precision shaping, airflows remain smooth where they matter most. Goals here focus tightly on stability, integration, and quiet performance behind the scenes. Starting with a spiral layout, one version takes shape through iterative modeling. A second approach builds on an intricate pathway, differing in structure yet matching function. Prototypes emerge from both concepts, each shaped by distinct spatial logic. Testing follows, though not mentioned here. Form guides fabrication in every case. Analyze thermal performance and surface homogeneity under varying flow rates. Beyond temperature control lies the challenge of preserving sterility. Maintaining body warmth must align with surgical cleanliness. A balance emerges when equipment setup supports both goals. Settings require adjustment based on environment and patient needs. Effectiveness hinges not only on devices used but also how they are positioned. Success shows in stable core temperatures and intact procedural boundaries.

This research introduces an approach unlike standard conductive pads resting atop surfaces - often awkward in layout - or air-based warmers prone to polluting clean zones. Built-in warming pathways sit within the table itself, enabling steady heat delivery while preserving unbroken sterile airflow and clear operative space. Lengthy operations benefit as individuals stay evenly warmed, distinct from surrounding conditions.

2. Material and Method

2.1. Experiment system

The aim of this study is to minimize the undesirable hypothermia that occurs in surgical processes by designing an operating table with water channels integrated into it. The study was carried out in the Heat Transfer Laboratory of the Department of Mechanical Engineering. In the experimental system, a wooden plate with dimensions of 500 × 500 × 30 mm was used, 16 mm wide channels were drilled on its surface with CNC and PVC hose was laid in these channels (7840 mm in design 1, 7220 mm in design 2). Thermocouples were placed in four different areas other than the inlet-outlet points, and the upper surface was covered with a 1 mm thick wood layer to provide thermal insulation. The hoses were connected to the hot water bath and the temperature data were transferred to the computer via the data acquisition device [26]. The experimental setup is presented in Figure 1. A thin slice of wood, just one millimeter thick, now covers the upper section to enhance how surfaces connect. Despite its naturally poor ability to conduct heat - ranging between 0.12 and 0.04 W/m·K- the timber behaves differently here: spreading warmth instead of blocking it. Because of this shift in function, areas that might have become uncomfortably warm due to hidden water pathways are kept even, reducing any danger during physical contact. Yet, this wooden layer serves only as a temporary solution. Down the line, once ready for medical use, it will give way to synthetic layers made from approved, body-safe plastics. These future alternatives must carefully walk the line - delivering heat quickly while ensuring harm never reaches the skin. Through selective engineering, their internal structure will favor both responsiveness and protection.

Figure 1. Image of the experimental setup

- **Operation Table**

Built to mirror real surgery conditions, this experiment used an actual operating table from Atatürk University Research Hospital. Only the rear part of the four-section layout was relevant, which led us to adjust the heater's form precisely around it. Each change taken through development followed clear medical requirements [26]. You will find engineering specifics in Table 1; Figure 2 shows how the setup is built. Many design hurdles came directly from strict health environment regulations. Our direction relied on temperature boundaries defined in ISO 80601-2-35 - skin contact past 43°C poses harm over time. Heat control in the device could not stray far due to this restriction. Still, decisions about design took form around it, guiding how warmth moves through the system. The standard did not suggest flexibility; neither could our response. Therefore, this study targets a controlled surface temperature range of 36–40 °C, utilizing a circulating fluid temperature of 42–50 °C to compensate for the thermal resistance of the pad material.

Figure 2. Operating table image taken as reference

Table 1. Operating table technical specifications

Parameter	Feature
Brand	Knives
Model	550S
Height (with cushion)	800 -1030 mm
Table Top	450-2020 mm
Table base	550-800 mm
Head section	450-310 mm
Back section	450- 550 mm
Seating section	450-445 mm
Foot Section (Right and Left)	215- 680 mm

Limitations: Wood was utilized in this study as a proof-of-concept material to simulate the thermal insulation required at the table base. It serves to direct heat flux upwards towards the patient. However, for clinical applications, this material will be replaced by medical-grade, biocompatible polymers or coated composites to ensure durability and compliance with hospital sterilization protocols.

- **Hot Water Bath**

In the hot water bath system used in the experiments, both the desired temperature can be adjusted and the flow rate is controlled. There is an operating temperature range of -25 ℃ to +150 ℃. The desired temperature value is reached shortly after entering the desired temperature value on the display panel. Flow rate control is adjusted between 1,2,3,4 and 5 stages. The image of the hot water bath used in the experimental system is given in Figure 3 and its technical specifications are given in Table 2.

Figure 3. Hot water bath used in the experimental system

Table 2. Hot water bath technical specifications

Parameter	Feature
Brand	Daihan Scientific, MaXircu CR-8)
Operating temperature	-25 °C – +150 °C
Accuracy	±%0.1 °C
Maximum flow rate	1500 l/h (with adjustment steps between 1-5)
Capacity	8 litres
Maximum viscosity	1000 centipoise
Maximum working pressure	7.5 psi
Insulation of the device	40 mm urethane foam

The pump stages were calibrated prior to the experiments. The flow rates corresponding to stages 1, 3, and 5 are 5 L/min, 15 L/min, and 25 L/min, respectively, demonstrating a linear control characteristic. The uncertainty in flow rate measurement was calculated to be ±2.0%.

- **Data Reading Card**

In the experimental system, Novus brand Field Logger data acquisition card was used, which instantaneously reads the temperature data obtained from the thermocouples placed on the operating table and transfers them to the computer. The device has 16 analogue inputs (8 universal, 8 thermocouple), 24-bit resolution, ±0.15% accuracy and 100 measurements per second per channel. Technical specifications are presented in Table 3 and the device image is presented in Figure 4. In the experiment, T-type copper-constantan thermoelements with a diameter of 0.25 mm were used. A total of 6 thermoelements with an accuracy of ± 0.05% °C were calibrated in a hot water bath and integrated into the system. Two thermoelements were placed at the hose connection points to measure the inlet and outlet temperatures, and the other four were placed on the operating table surface.

Figure 4. Data reading card used in the experimental system

2.2. Experiment model

For square plates with a side length of 500 mm and a thickness of 30 mm, the designs were modelled in three dimensions in SolidWorks by calculating the maximum channel length that can be placed inside. According to these models, 16 mm wide channels were drilled on wood CNC machines. In the first design, the exit point was drilled from a point close to the centre of the plate and provided from the bottom. In the second design, the outlet channel was positioned in the same direction as the inlet [26]. The channel width of 16 mm was selected to accommodate the 13 mm outer diameter of the flexible PVC tubing, allowing for a secure press-fit without compressing the flow cross-section. The complex layout of Plate 2 was designed to maximize the heat transfer surface area within the 500x500 mm footprint. Machined plate images based on SolidWorks drawings of both designs are presented in Figure 5.

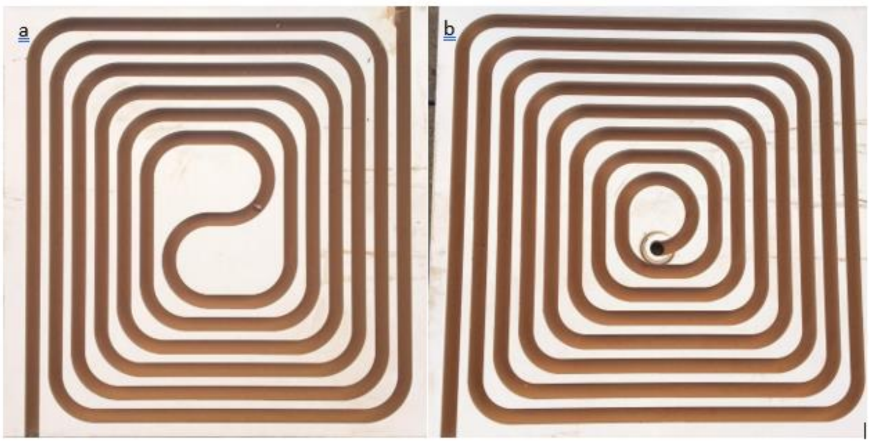

Figure 5. a) 1st Experimental Model b) 2nd Experimental Model

- **PVC hose**

PVC hose was selected due to the radii and holes used in the designs. The outer diameter of the hoses used is 13 mm and the inner diameter is 10 mm. The heat conduction coefficient is 0.16 W/mK. A total of 15 metres of hoses were laid on wooden planks. The laying of the hoses on the plate is shown in Figure 6.

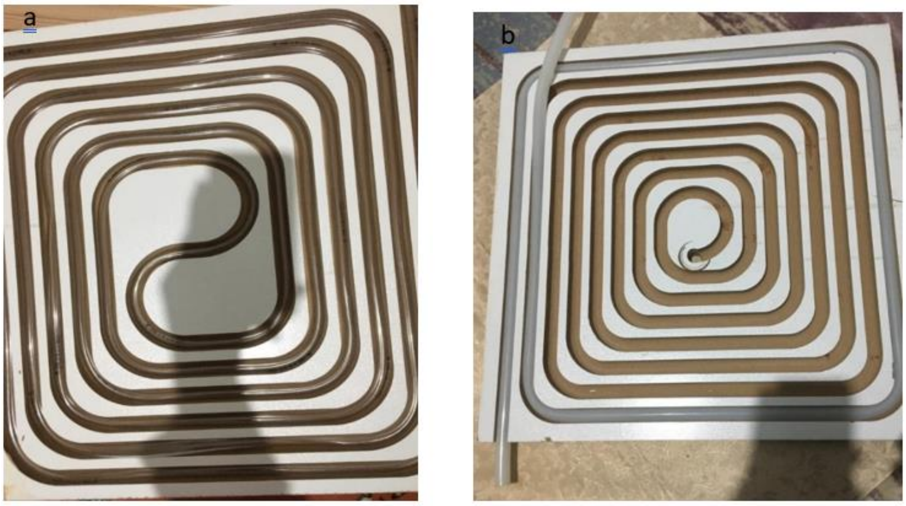

Figure 6. a) 1st Experimental Model (Plate 1) with pvc hose laid b) 2nd Experimental Model (Plate 2) with pvc hose laid

2.3. Calculations

The internal flow (inside the pipe or duct) can be laminar or turbulent according to the flow conditions [26,27].

Reynolds number (Re) in a circular pipe; $\mathrm{Re} = \frac{\rho V_{avg} D}{\mu}$

It is expressed in the form. In the equation V_{avg} is the average flow velocity, D is the diameter of the pipe, $\upsilon = \mu/\rho$ is the kinematic viscosity of the flow. The mean flow velocity (V_{avg}) was calculated from the volumetric flow rate ($\dot{V}$) using the continuity equation: $V_{avg} = \dot{V} / Ac$, where Ac is the cross-sectional area of the pipe.

When the Re ≤ 2300, the flow is laminar and when Re >10000, the flow is turbulent. The experiments were conducted in a Reynolds number range of 4000-25000. Since Re > 2300, the flow is fully within the turbulent regime, justifying the use of the Petukhov and Colburn correlations for comparison.

When the fluid is turbulent flow, friction coefficients and heat transfer relations are utilized from experimental studies.

Friction factor in smooth pipes; $f=(0.790\ln \mathrm{Re} - 1.64)^{-2}$

It is found from the first Petukhov equation. The Nusselt Number (Nu) is related to the friction factor from the Chilton-Colburn analogy; $Nu=0.125\times f \times Re\times Pr^{1/3}$

is expressed. The Colburn equation can be obtained from the connection of the friction factor $f=0.184\times Re^{-0.2}$ law. This equation; $Nu= 0.023\times Re^{0.8}\times Pr^{n}$ is found. In the connection, n = 0.4 can be taken as heating the flow flow through the pipe, and in the case of n = 0.3, the flow can be taken as cooling and this connection is known as the Dittus-Boelter equation.

An experimental uncertainty analysis was conducted to determine the reliability of the results using the standard error propagation method. The uncertainty for the direct temperature measurements was determined to be ±0.1 °C, while the uncertainty for the volumetric flow rate was ±2.0%. Based on these primary measurement errors, the maximum propagated uncertainties for the calculated dimensionless parameters were evaluated. Consequently, the uncertainty for the Reynolds number (Re) was calculated as ±3.5%, and the uncertainty for the Nusselt number (Nu) was determined to be ±4.2%.

3. Results and Discussion

In this study, experimental analyses were carried out at different temperatures and pump stage levels to evaluate the heating performance for hypothermia prevention. Three different temperature values (42 °C, 47 °C, and 50 °C) and three different pump stages (1st, 3rd and 5th stage) of the hot water bath system were used in the experiments. The experimental parameters are summarized in Table 3. The data obtained at different temperature and flow rate (pump stage) combinations were measured experimentally and visualized and evaluated by means of graphs. Looking at these charts reveals how rising temperature and changes in pump speed influence the patient's body heat. Flow conditions during testing led to Reynolds numbers between 4000 and 25000. Within this span, movement of liquid turns mostly chaotic. A key observation: odd channel geometry pushes flow toward disorder. Mixing improves noticeably within low Reynolds conditions because heat transfer rates climb beyond typical predictions for smooth, steady flows. When temperatures increase along with pump intensity, outcomes shift sharply, thermal response links directly to both inlet heat levels and pumping strength. Performance patterns grow clearer under those combined high inputs. Visual analysis helped reveal how measurements changed across test runs. The link between operating choices and heating speed became obvious through plotted results. Higher settings did not just add effect, they altered behavior entirely.

Table 3. Flow Amounts According to Pump Stage Level Values

Pump Stage	Level 1st	Level 3rd	Level 5th
Flow Amounts (lt/min)	5 lt/min	15 lt/min	25 lt/min

With preparations complete, the first five pump stages adjusted to specific flow volumes. Shown in Table 3, each stage's data reveals how speed directly shapes volume output. Because outputs rose steadily with speed, adjustments during testing stayed accurate. Fluid behavior remained predictable thanks to this steady pattern across runs.

3.1. Experiments conducted for Plate 1

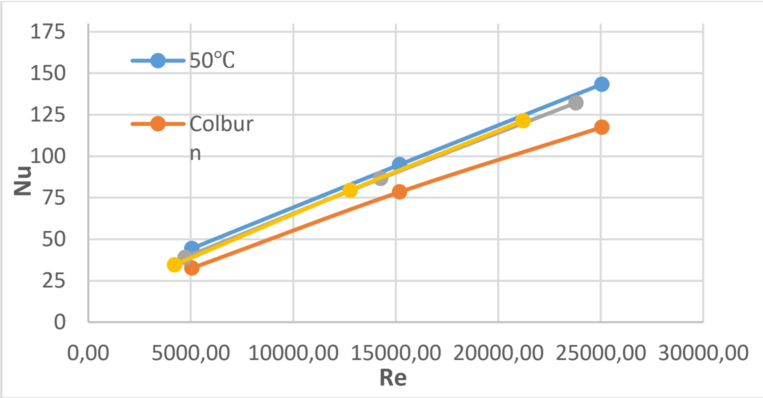

Figure 7. Comparison of Nu-Re graphs at different temperatures in Plate 1 model

Looking closer at Figure 7, insights emerge about what drives heat transfer performance on Plate 1. Agreement appears strong when comparing results to established forced convection principles often referenced in studies [27–30], particularly through how Nu and Re numbers align. As fluid speed increases, so does the Reynolds number- this rise ties clearly to a climbing Nusselt value seen in tests.

Speed increases bring a narrower edge zone, yet turbulence grows, setting the pattern seen throughout. Its unique outline lets Plate 1 manage disorderly eddies well, especially at low pump settings. Unlike ordinary flat versions, this trait raises heat transfer clearly [31]. Flow quickened after inlet fluid reached 50 °C, since dense drag faded while spinning motions developed smoother. Highest performance occurs only when warmth climbs as flow rate shifts- supporting prior estimates in [32] - but results change should timing drift.

Matters like these weigh heavy in practice whenever warmth must stay with patients through treatments- going well beyond numbers on a screen. Low core temps during operations link to tougher recoveries, along with greater chance of issues after the fact [5,33,34]. Since they guide liquid flow precisely, tools like Plate 1 enhance how heat moves, helping it seep deeper into bodily layers. Yet spots may still overheat or cool down too much if air doesn't move right or warmth isn't shared evenly across zones [35,36]. Still, checking heat release alongside how fluids move shapes much of the design work. From Plate 1, data shows clear reactions when flow changes happen. Because the plate stirs up chaos in the liquid, transferring warmth jumps- just like predictions said it would. Most striking? How tightly actual tests follow past math estimates.

3.2. Experiments conducted for Plate 2

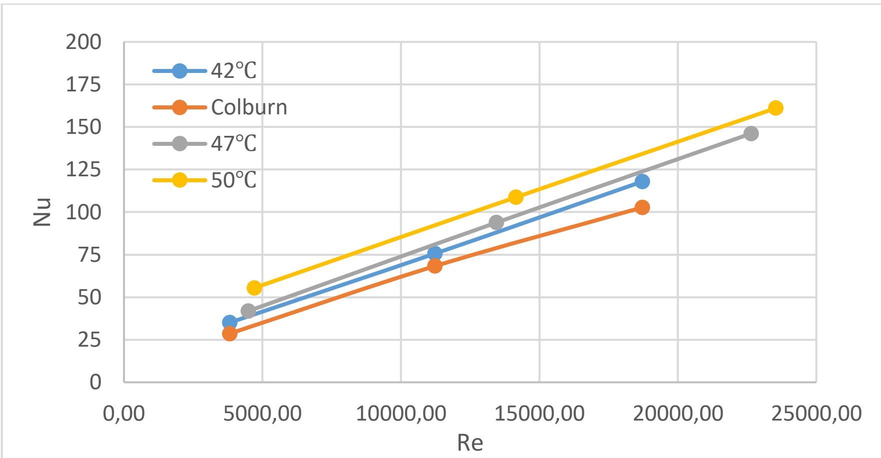

Figure 8. Comparison of Nu-Re graphs at different temperatures in Plate 2 model

Picture 8 shows the link between Nu and Re on Plate 2 across various pump levels and temps - 42°C, then 47°C, after that 50°C. As Re climbs, so does Nu, clearly. Such behavior fits known patterns of forced flow seen before [27]. At slow flows too, Plate 2 runs stronger than typical models predict. Instead of matching Colburn's rule, measured Nu lands higher. It's mostly the shape of the plate that leads to this shift. Because of how the plate is shaped, turbulence appears sooner, which breaks up the smooth growth of the airflow near the surface [31]. Higher convective heat transfer happens when pump stages 3 and 5 push harder, once flow turns chaotic, and as warmth makes the liquid thinner. When compared to others, the Colburn model lined up best with real-world data; meanwhile, Petukhov's set a kind of ceiling based on theory. Small differences might come from slight flaws in the test setup's surface finish.

What we found really matters for building better medical devices, especially machines that move fluids outside the body where heating must be fast and steady. Staying at normal body temperature during operations has long been linked to fewer infections and quicker healing [3,5,37]. Because of this, the strong heat control seen in Plate 2 supports solid design work for therapies needing precise warmth management, such as treating cancer with heat[19,23].

Tests prove adjusting pump speed and temperature carefully pushes better heat flow. Results suggest it might handle tough cooling jobs in factories and medical tools, beyond just checking old methods. What you see in Plate 2 works well because of how it's shaped. Sharp, tight turns appear often in Plate 2- unlike smoother coils seen before. Spinning inside every bend, the flow creates small swirls known as Dean vortices because of how inertia pushes outward. Because of these twists, the liquid keeps shifting positions, never letting heat settle into a steady outer zone. With constant mixing happening, the wall sees sharper changes in temperature across its surface. That shift means more efficient transfer overall- evident in much higher Nusselt values measured.

3.3. Comparative analysis of plate 1 and plate 2

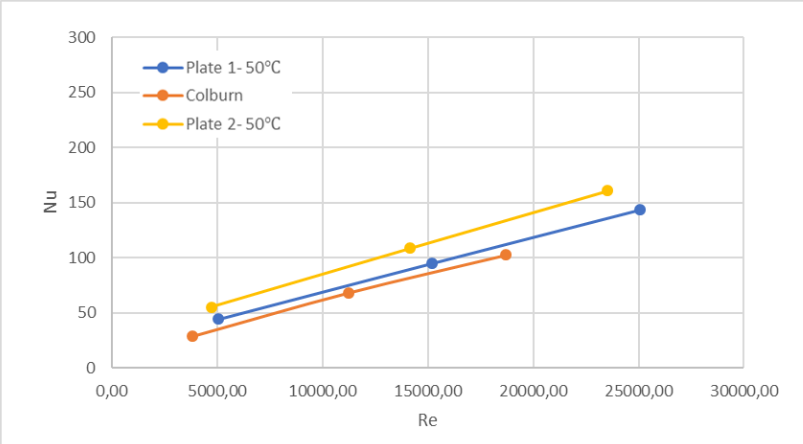

Figure 9. Comparison of experimental models when the temperature is 50 °C

One look at Figure 9 shows how the two plate shapes behave under forced airflow, hinting at uses in tech and medicine. As basic principles would predict, higher flow speed led to much stronger heat transfer on both designs [27].

Heat transfer improved noticeably with Plate 2, particularly when pump intensity and temperature rose. Its shape played a key role - breaking up boundary layers more efficiently while boosting turbulent activity [31]. Instead of following typical patterns, Plate 1 lined up roughly with the Colburn model but lagged slightly under low-flow conditions because turbulence stayed weak. Farther ahead in performance, Plate 2 moved beyond Colburn's estimates, drawing near the Petukhov limit, suggesting stronger blending within the fluid stream [38].

Despite the heat, thinner fluids moved easier through both designs, yet Plate 2 reacted more sharply. Heat traveled faster across Plate 2, though its sharp turns slowed pressure harder than in Plate 1. When warming patients before surgery, speed matters just as much as temperature. Thanks to smarter pumping, delays faded. Flow stayed strong all along. Higher Nusselt numbers on Plate 2 mean heat reaches the skin more rapidly. Because of anesthesia, body temperature often drops sharply at first. This design helps fight that drop. These higher values do more than improve efficiency. They act as a safeguard when it matters most. When the body loses internal warmth right after sedation begins, the system responds faster. That speed makes it possible to restore normal temperature sooner. All of this happens without pushing fluid temps into risky ranges.

Different shapes suit different uses. While Plate 1 fits standard tasks with modest demands, Plate 2 works better in advanced medical setups like ECMO or heated therapy devices. Because of its high heat transfer efficiency, Plate 2 supports warming systems that maintain body temperature during surgery [3,5,23].

Starting off, Plate 2 handles heat better because of how it twists the flow sharply. Each tight U-turn flings fluid outward using centrifugal push, spinning up swirls called Dean vortices along the way. Swirling sideways across the stream, these eddies stir things up right where heat usually gets stuck. That constant churning breaks apart the insulating film that would otherwise slow down heat transfer. Meanwhile, Plate 1 takes a gentler path with its coiling channel, letting a thicker buffer form. This steady cloak resists temperature changes by acting like a shield against energy movement.

Watch how Plate 2 moves heat more effectively yet stumbles with higher pressure drops because of tight, frequent bends. Still, when warming patients before surgery, what matters most is how fast heat transfers. Even with added resistance, the pump managed well, keeping flow steady, which makes the complex shape worthwhile. Flow stays strong over wider ranges thanks to smart guiding paths built into Plate 2's layout. Results line up closely with established models, showing that pairing surface patterns with fluid behavior fits real-world demands better. What counts shows clearly when test numbers mirror predictions.

In Figure 10, thermal images taken at 50 ℃ in the 1st plate model are visualised. Looking at the images, the increase in flow rate increased the surface temperature. This situation shows that it is compatible with the experiments performed. In Figure 11, the thermal images taken at 50 ℃ in the 2nd plate model are visualised. Looking at these images, the increase in flow rate increased the surface temperature. This shows that the experiments are in agreement. When Figure 10 and Figure 11 are compared among themselves, it is understood from the images that the surface temperature value is higher in the 2nd Plate module. Tests showed it matched what we saw in trials. From heat maps, Plate 2 spreads warmth more evenly than Plate 1. Across the heated area, the highest variation measured was close to ±0.8°C on Plate 2. Even heating matters a lot in medical settings- keeps any one spot from getting too hot, avoids burns, yet still warms fully where needed. So, using the second plate design as part of an operation table makes sense. Looking at the numbers from the heat pictures (Fig. 11), Plate 2 reached an average warmth of 39.2 °C, spreading across its face with little difference- just plus or minus 0.4 °C. Not so steady is Plate 1, where temps swing wider by ±0.9 °C; clearly, Plate 2 keeps things more even. That steadier spread means hotspots or cold spots are less likely to pop up out of nowhere.

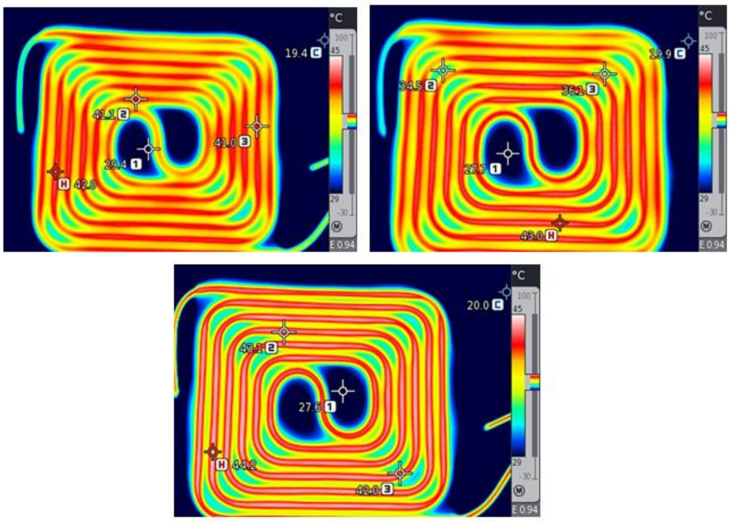

Figure 10. 1. Thermal images at different flow rates at 50℃ in the plate model

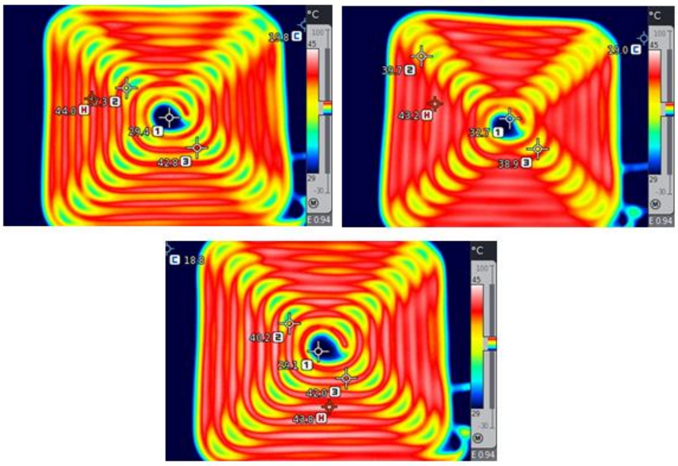

Figure 11. 2. Thermal images at different flow rates at 50℃ in plate model

4. Conclusions and Recommendations

In the analyses performed on Plate 1, it was determined that the Reynolds number (Re) increased with the pump stage and a regular increase in the Nu was observed in response to this increase. This indicates that the heat convection coefficient increases with the increase in the degree of turbulence of the flow. The results obtained, especially in the 5th stage, showed values very close to the Dittus-Boelter and Petukhov correlations. This shows that the system can be explained by a linear heat transfer model. In the experiments on Plate 2, the Nu-Re relationship showed positive correlation in all three pump stages. Especially, the Nu obtained at the 3rd and 5th stages exceeded the classical Colburn equation and revealed that the heat transfer performance of the system increased. This indicates that the flow disturbances and turbulence levels created by the plates significantly increase the convective heat transport in the pipe. It is also found that the heat convection coefficient increases with temperature at higher pump stages.

Compared to the literature, the experimental data show significant similarity with forced convection models in both engineering applications and biomedical systems. In particular, the agreement with the correlations reported by Petukhov (1970) [30] and Incropera et al. (2007) [38] once again supports the validity of classical empirical formulae in such internal flow systems. Moreover, high flow rates and efficient heat transfer are critical in biomedical applications, especially in blood cooling systems and devices containing heat exchangers. Based on the results, the following design rules for operating table heating are proposed: (1) Complex flow paths with frequent directional changes are superior for compact surfaces; (2) An inlet temperature of 50°C at flow rates corresponding to Re > 15,000 provides the optimal balance between rapid warming and safety.

As a result, it is observed that the heat convection coefficient increases linearly with Re in the analyses performed for both Plate 1 and Plate 2 and is highly consistent with classical correlations. This reveals the importance of supporting these correlations with experimental verification during the design process in terms of system performance. This study can make significant contributions in the fields of bioengineering, energy systems and heat exchanger design.

This experimental study investigated in detail the heat transfer characteristics of different geometries of plate designs with hot water passage. The results show that inlet temperature and flow rate have a significant effect on the Nu. In particular, the Plate 2 model exhibited superior heat transfer performance, which became evident with increasing Re. Thermal analyses confirmed that the surface temperature increases with increasing flow rate, demonstrating the potential for controlled heating. In conclusion, the use of the Plate 2 model for maintaining patient body temperature in operating table applications can be considered as a suitable alternative due to its effective heat transfer capacity.

Future studies may focus on the optimization of the system with different fluid types and more complex geometries. While the use of PVC hoses (k = 0.16 W/mK) limited the overall heat transfer coefficient compared to potential metallic solutions, it was necessary to accommodate the complex geometric constraints of the flow channels, particularly in Plate 2. Future work will focus on: (i) Computational Fluid Dynamics (CFD) simulations to optimize the bend angles; (ii) Experimental validation using tissue-mimicking phantoms to measure heat transfer to the human body; and (iii) Testing with biocompatible, medical-grade composite materials. Future designs will focus on high-conductivity flexible composites to minimize thermal resistance.

Nomenclature

Nu : Nusselt Number
Re : Reynolds Number
f : Friction Factor
V_{ort}: Average flow velocity
D : Diameter of the pipe
Pr : Prandtl Number

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics in Publishing

There are no ethical issues regarding the publication of this study

Acknowledge

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