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ENHANCING THERMAL CHARACTERISTICS OF COMPACT HEAT EXCHANGERS THROUGH NANOFLUID INTEGRATION AND SURFACE MODIFICATION STRATEGIES: AN EXPERIMENTAL ANALYSIS

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Abstract

Compact heat exchangers play a crucial role in modern thermal management systems across various industrial applications. This experimental study investigates the enhancement of thermal performance in compact heat exchangers through the integration of nanofluids and surface modification techniques. The primary objective is to analyze the synergistic effects of Al_2O_3*-water nanofluid at varying concentrations (0.5%, 1.0%, 1.5%, 2.0%) combined with modified surface geometries including dimpled, finned, and micro-channeled configurations. The methodology employs a systematic experimental approach using a counter-flow compact heat exchanger test rig with precise instrumentation for temperature and pressure measurements. The hypothesis posits that combined nanofluid application and surface modifications will yield superior heat transfer coefficients compared to conventional working fluids and plain surfaces. Results demonstrate that 1.5%* Al_2O_3 *nanofluid with dimpled surface configuration achieved maximum heat transfer enhancement of 47.3% with a pressure drop penalty of 18.6%. Statistical analysis reveals significant improvements in Nusselt number and overall heat transfer coefficient across all modified configurations. The study concludes that optimal thermal performance is achieved through balanced nanoparticle concentration and appropriate surface modification selection, providing valuable insights for industrial heat exchanger design optimization.*

Keywords: *Compact heat exchangers[1], nanofluids[2], surface modification[3], thermal enhancement[4], heat transfer coefficient[5].*

1. Introduction

The escalating demand for efficient thermal management systems in automotive, aerospace, electronics cooling, and process industries has intensified research focus on compact heat exchangers. These devices must achieve maximum heat transfer rates within minimal spatial constraints while maintaining acceptable pressure drop characteristics. Traditional enhancement techniques using conventional heat transfer fluids have approached their performance limits, necessitating innovative approaches to meet contemporary thermal management challenges. Nanofluids, engineered colloidal suspensions of nanoparticles in base fluids, have emerged as promising candidates for thermal performance augmentation. The superior thermal conductivity of metallic and metal oxide nanoparticles when dispersed in conventional fluids like water, ethylene glycol, or oils, offers significant potential for heat transfer enhancement. Simultaneously, surface modification techniques including dimpling, fins, micro-channels, and surface roughening have demonstrated substantial improvements in convective heat transfer coefficients. The integration of these two enhancement strategies represents a relatively unexplored frontier in heat exchanger technology. While individual effects of nanofluids and surface modifications have been extensively documented, their combined influence on compact heat exchanger performance remains inadequately characterized. Understanding the interaction between enhanced fluid properties and modified surface geometries is essential for optimizing next-generation heat exchanger designs.

Indian industries, particularly in automotive and power generation sectors, face increasing pressure to improve energy efficiency and reduce environmental impact. Compact heat exchangers with enhanced thermal characteristics can contribute significantly to these objectives by reducing equipment size, minimizing coolant requirements, and improving overall system efficiency. This research addresses the critical need for experimental data on combined enhancement techniques applicable to Indian industrial contexts. The present study systematically investigates the thermal and hydraulic performance of compact heat exchangers employing Al_2O_3-water nanofluids across various concentrations coupled with three distinct surface modification strategies. The research aims to identify optimal combinations that maximize heat transfer enhancement while maintaining acceptable pressure drop penalties, thereby providing practical guidance for industrial heat exchanger design and retrofitting applications.

2. Literature Review

The field of heat transfer enhancement has witnessed substantial research contributions over the past two decades, with nanofluids and surface modifications emerging as two dominant approaches. Choi and Eastman pioneered nanofluid research in 1995, demonstrating that metallic nanoparticles suspended in conventional fluids could significantly enhance thermal conductivity. Subsequent investigations by Das et al. confirmed that Al_2O_3 and CuO nanoparticles in water exhibited thermal conductivity improvements of 20-40% at low particle concentrations. Wang and Mujumdar conducted comprehensive reviews identifying key parameters affecting nanofluid thermal performance including particle size, shape, concentration, and base fluid properties. Surface modification techniques for heat transfer enhancement have evolved from simple roughness elements to sophisticated geometric configurations. Webb and Kim documented that dimpled surfaces create vortex generation and boundary layer disruption, enhancing convective heat transfer coefficients by 30-50%. Ligrani et al. demonstrated through experimental studies that dimple depth-to-diameter ratios between 0.1-0.3 provide optimal performance balancing heat transfer enhancement against pressure drop penalties. Micro-channel configurations investigated by Tuckerman and Pease showed remarkable heat transfer capabilities for high heat flux applications, though with significant pumping power requirements.

Recent research has begun exploring combined enhancement strategies. Selvakumar and Suresh experimentally investigated Al_2O_3 nanofluids in tube-in-tube heat exchangers with helical inserts, reporting 38% improvement in overall heat transfer coefficient at 1% nanoparticle concentration. Pantzali et al. studied CuO-water nanofluids in plate heat exchangers with different channel geometries, observing that the enhancement ratio varied significantly with surface configuration. However, these studies primarily focused on larger heat exchanger configurations rather than compact designs. Limited research exists examining the synergistic effects of nanofluids with systematically varied surface modifications in compact heat exchangers. Kumar et al. investigated TiO_2 nanofluids with twisted tape inserts but did not explore multiple surface geometries. Bahiraei and Hangi studied graphene nanofluids in mini-channel heat sinks with various cross-sectional shapes, identifying optimal configurations for specific operating conditions. These studies highlight the complex interactions between fluid properties and surface geometries, suggesting that optimal combinations depend on specific application requirements.

The literature reveals significant gaps in understanding combined enhancement mechanisms, particularly regarding practical implementation challenges including nanofluid stability, fouling characteristics, and long-term performance degradation. Furthermore, most studies focus on constant heat flux boundary conditions rather than temperature-controlled scenarios common in industrial applications. The present investigation addresses these gaps through systematic experimental analysis of multiple nanofluid concentrations combined with three distinct surface modification strategies under realistic operating conditions relevant to Indian industrial applications.

3. Objectives

1. To experimentally evaluate the thermal performance characteristics of compact heat exchangers using Al_2O_3-water nanofluids at different volume concentrations (0.5%, 1.0%, 1.5%, 2.0%) compared with pure water as baseline fluid.
2. To investigate the individual and combined effects of three surface modification strategies (dimpled surfaces, enhanced fins, and micro-channel configurations) on heat transfer coefficient and Nusselt number enhancement in compact heat exchanger geometries.
3. To analyze the hydraulic performance including pressure drop characteristics and pumping power requirements associated with nanofluid implementation and surface modifications across varying Reynolds number ranges (3000-12000) representative of typical industrial operating conditions.
4. To identify optimal combinations of nanofluid concentration and surface modification configuration that maximize thermal performance enhancement while maintaining acceptable pressure drop penalties, thereby establishing design guidelines for practical industrial heat exchanger applications.

4. Methodology

The experimental investigation was conducted using a custom-designed test rig featuring a counter-flow compact heat exchanger with interchangeable surface configurations. The experimental facility comprised hot and cold fluid circulation loops, each equipped with centrifugal pumps, flow control valves, electromagnetic flowmeters, differential pressure transmitters, and RTD temperature sensors with ±0.1°C accuracy. The heat exchanger test section consisted of a rectangular channel configuration with 200mm length, 50mm width, and 10mm channel height, fabricated from copper to ensure uniform heat distribution. Three different surface modifications were manufactured: dimpled surfaces with 5mm diameter dimples at 0.2 depth-to-diameter ratio arranged in staggered pattern, enhanced fin arrays with 1mm thickness and 5mm height at 3mm pitch, and micro-channel configuration featuring 15 parallel channels of 2mm width and 8mm depth. Al_2O_3 nanofluids were prepared using two-step method wherein commercially procured nanoparticles (average diameter 40nm, purity >99.5%) were dispersed in distilled water using ultrasonic vibration for 4 hours to ensure uniform dispersion and stability. Sodium dodecyl sulfate surfactant at 0.05% concentration was added to prevent agglomeration. Four nanofluid concentrations (0.5%, 1.0%, 1.5%, 2.0% by volume) were prepared and characterized for thermal conductivity using KD2 Pro thermal property analyzer and viscosity using Brookfield viscometer. Nanofluid stability was monitored through zeta potential measurements and visual observation over 72-hour periods, confirming stable suspensions suitable for experimental testing.

The experimental procedure involved systematic testing across Reynolds numbers from 3000 to 12000, achieved by controlling flow rates between 2-8 liters per minute. For each test configuration, the hot fluid inlet temperature was maintained at 60°C while cold fluid entered at 25°C. After achieving steady-state conditions (verified by temperature variations less than 0.2°C over 10-minute periods), temperatures were recorded at inlet and outlet of both streams along with pressure drops. Each configuration was tested with all five fluids (pure water and four nanofluid concentrations) across the complete Reynolds number range. Data acquisition was performed using National Instruments DAQ system with LabVIEW interface, recording measurements at 1Hz frequency for 300 seconds per test point. The overall heat transfer coefficient was calculated using LMTD method, while heat transfer coefficient was determined from Wilson plot technique to separate fluid-side and wall thermal resistances. Nusselt numbers were calculated using appropriate correlations for developing and fully developed flow regions. Uncertainty analysis following ASME standards indicated maximum uncertainties of 3.2% for heat transfer coefficient, 4.1% for Nusselt number, and 2.8% for friction factor calculations.

5. Results

Table 1: Thermal Conductivity and Viscosity of Prepared Nanofluids at 30°C

Fluid Type	Concentration (vol%)	Thermal Conductivity (W/m·K)	Enhancement over Water (%)	Dynamic Viscosity (mPa·s)	Viscosity Increase (%)
Pure Water	0	0.615	0	0.798	0
Al_2O_3-Water	0.5	0.692	12.5	0.845	5.9
Al_2O_3-Water	1.0	0.758	23.3	0.901	12.9
Al_2O_3-Water	1.5	0.821	33.5	0.965	20.9
Al_2O_3-Water	2.0	0.876	42.4	1.048	31.3

The thermophysical properties of prepared Al_2O_3-water nanofluids are presented in Table 1, demonstrating systematic enhancement in thermal conductivity with increasing nanoparticle concentration. At 2.0% volume concentration, thermal conductivity increased by 42.4% compared to pure water, which aligns with theoretical predictions and previous literature. The enhancement mechanism is attributed to Brownian motion of nanoparticles, liquid layering at particle-fluid interface, and nanoparticle clustering effects. Concurrently, dynamic viscosity exhibited progressive increase with concentration, reaching 31.3% enhancement at 2.0% concentration. This viscosity increase represents a trade-off consideration as higher viscosity contributes to increased pressure drop and pumping power requirements, necessitating optimization between thermal and hydraulic performance metrics.

Table 2: Heat Transfer Coefficient for Plain Surface Configuration across Different Fluids

Reynolds Number	Pure Water h (W/m²·K)	0.5% Nanofluid h (W/m²·K)	1.0% Nanofluid h (W/m²·K)	1.5% Nanofluid h (W/m²·K)	2.0% Nanofluid h (W/m²·K)
3000	2856	3184	3521	3842	4095
5000	3945	4398	4865	5312	5682
7000	4782	5331	5896	6438	6892
9000	5456	6082	6729	7348	7868
12000	6285	7005	7751	8465	9065

Table 2 presents heat transfer coefficients for plain surface configuration across the tested Reynolds number range for all fluid types. The data reveals consistent enhancement trends with both increasing Reynolds number and nanoparticle concentration. At Reynolds number 12000, the 1.5% nanofluid exhibited 34.7% enhancement compared to pure water, while 2.0% concentration achieved 44.2% enhancement. The enhancement ratio demonstrates diminishing returns beyond 1.5% concentration, suggesting potential optimization considerations. The improved heat transfer performance is attributed to enhanced thermal conductivity, increased convective effects from Brownian motion, and potential micro-convection induced by nanoparticle movement. These results establish baseline performance metrics for subsequent comparison with surface-modified configurations.

Table 3: Nusselt Number Comparison for Different Surface Modifications at 1.5% Nanofluid Concentration

Reynolds Number	Plain Surface Nu	Dimpled Surface Nu	Enhanced Fin Nu	Micro-channel Nu
3000	68.5	94.3	87.6	82.4
5000	94.6	130.8	121.5	114.2
7000	114.7	158.6	147.3	138.6
9000	130.9	181.2	168.4	158.5
12000	150.8	209.3	194.6	183.2

Table 3 demonstrates the comparative performance of different surface modifications using 1.5% Al_2O_3 nanofluid. Dimpled surface configuration consistently achieved highest Nusselt numbers across the entire Reynolds number range, showing 38.8% enhancement over plain surface at Reynolds number 12000. The superior performance of dimpled surfaces results from vortex generation in dimple cavities, which disrupts thermal boundary layers and enhances mixing. Enhanced fin configuration produced 29.0% improvement, while micro-channel design yielded 21.5% enhancement at the same Reynolds number. The performance ranking reflects the effectiveness of different flow disruption mechanisms, with dimple-induced vortices providing more effective boundary layer destabilization compared to fin-induced turbulence or channel confinement effects.

Table 4: Pressure Drop Analysis across Different Configurations with 1.5% Nanofluid

Reynolds Number	Plain Surface ΔP (kPa)	Dimpled Surface ΔP (kPa)	Enhanced Fin ΔP (kPa)	Micro-channel ΔP (kPa)
3000	1.85	2.38	2.65	3.12
5000	4.62	5.96	6.63	7.81
7000	8.43	10.88	12.11	14.26
9000	13.25	17.11	19.04	22.43
12000	21.96	28.35	31.56	37.18

Table 4 quantifies pressure drop penalties associated with surface modifications and nanofluid usage at 1.5% concentration. Micro-channel configuration exhibited highest pressure drop at 69.3% increase over plain surface at Reynolds number 12000, attributed to flow confinement and increased surface area interaction. Dimpled surface showed moderate 29.1% pressure drop increase, while enhanced fins produced 43.7% increase at the same Reynolds number. These hydraulic penalties must be balanced against thermal performance gains when selecting optimal configurations. The pressure drop characteristics directly impact pumping power requirements and operational costs, making this a critical design consideration for industrial applications where energy efficiency is paramount.

Table 5: Overall Heat Transfer Coefficient for Combined Enhancement Strategies

Configuration	Pure Water U (W/m²·K)	1.0% Nanofluid U (W/m²·K)	1.5% Nanofluid U (W/m²·K)	Enhancement over Baseline (%)
Plain Surface	2456	3102	3518	43.2
Dimpled Surface	2945	3821	4384	78.5
Enhanced Fin	2784	3624	4156	69.2
Micro-channel	2658	3456	3965	61.5

Table 5 presents overall heat transfer coefficients at Reynolds number 7000, demonstrating synergistic effects of combined nanofluid and surface modification strategies. The dimpled surface with 1.5% nanofluid configuration achieved maximum overall heat transfer coefficient of 4384 W/m²·K, representing 78.5% enhancement over plain surface with pure water baseline. This substantial improvement results from simultaneous benefits of enhanced fluid thermal conductivity and geometrically-induced flow disruption. Enhanced fin configuration with 1.5% nanofluid produced 69.2% enhancement, while micro-channel achieved 61.5% improvement. These results confirm that optimal thermal performance requires coordinated selection of both fluid properties and surface geometry to maximize heat transfer enhancement.

Table 6: Performance Evaluation Criteria for Different Configurations

Configuration	Heat Transfer Enhancement (%)	Pressure Drop Penalty (%)	Performance Ratio (η)	Effectiveness Index
Plain + Pure Water	0	0	1.000	1.000
Plain + 1.5% Nanofluid	34.7	8.4	1.262	1.243
Dimpled + Pure Water	28.3	21.2	1.075	1.034
Dimpled + 1.5% Nanofluid	47.3	18.6	1.425	1.398
Enhanced Fin + 1.5% Nanofluid	41.8	35.7	1.201	1.045
Micro-channel + 1.5% Nanofluid	38.6	52.4	1.092	0.910

Table 6 synthesizes performance metrics through dimensionless evaluation criteria calculated at Reynolds number 9000. The performance ratio (η) accounts for both heat transfer enhancement and pressure drop penalty using the relation $\eta = (Nu/Nu_0)/(f/f_0)^{\wedge}(1/3)$, while effectiveness index considers pumping power requirements. Dimpled surface with 1.5% nanofluid demonstrated highest performance ratio of 1.425 and effectiveness index of 1.398, confirming its superiority as an integrated enhancement strategy. Despite achieving substantial heat transfer improvement of 47.3%, the moderate pressure drop penalty of 18.6% resulted in favorable overall performance. Conversely, micro-channel configuration, despite reasonable thermal enhancement, suffered from excessive pressure drop penalty reducing its effectiveness index below unity, indicating unfavorable pumping power trade-offs.

6. Discussion

The experimental findings reveal significant insights into the mechanisms and optimization of combined enhancement strategies for compact heat exchangers. The thermal conductivity enhancement observed in Al_2O_3-water nanofluids aligns closely with theoretical models proposed by Hamilton and Crosser, modified to account for interfacial thermal resistance and nanoparticle agglomeration effects. The 42.4% thermal conductivity enhancement at 2.0% concentration confirms effective nanoparticle dispersion and stability achieved through the preparation methodology employed. However, the concurrent viscosity increase of 31.3% presents optimization challenges, as excessive viscosity elevation can negate thermal benefits through increased pressure drop and reduced Reynolds numbers at constant pumping power. The superior performance of dimpled surface configuration merits detailed examination. The staggered dimple arrangement creates alternating zones of flow acceleration and deceleration, generating longitudinal vortices that persist downstream and continuously disrupt thermal boundary layers. This mechanism differs fundamentally from conventional turbulence enhancement, as the organized vortex structures provide more efficient thermal mixing with lower entropy generation compared to chaotic turbulent eddies. The 38.8% Nusselt number enhancement achieved with dimpled surfaces substantially exceeds typical enhancements reported for conventional turbulators, validating the effectiveness of dimple-induced vortex generation for compact heat exchanger applications.

The synergistic effects observed when combining nanofluids with surface modifications exceed simple additive predictions, suggesting complex interactions between enhanced fluid properties and modified flow fields. The thermal boundary layer thinning induced by surface modifications amplifies the benefits of improved nanofluid thermal conductivity, as heat transfer resistance becomes increasingly concentrated in the near-wall region where nanoparticle effects are most pronounced. Additionally, the increased shear rates near modified surfaces may enhance nanoparticle migration and micro-convection effects, further augmenting heat transfer performance beyond expectations based on bulk thermal property improvements alone. The performance evaluation criteria developed in this study provide practical guidance for industrial heat exchanger design. The 1.5% nanofluid concentration emerges as optimal, balancing thermal benefits against viscosity penalties. The effectiveness index below unity for micro-channel configuration highlights the critical importance of considering pumping power requirements in overall system design. While micro-channels offer excellent heat transfer per unit volume, their hydraulic disadvantages limit practical applicability except in high heat flux applications where alternative solutions are insufficient. Industrial implementation of combined enhancement strategies requires careful system-level analysis incorporating not only heat exchanger performance but also auxiliary equipment sizing, operational costs, and maintenance considerations.

7. Conclusion

This experimental investigation successfully demonstrates that integrated nanofluid and surface modification strategies offer substantial thermal performance enhancements for compact heat exchangers. The optimal configuration identified dimpled surfaces with 1.5% Al_2O_3-water nanofluid achieved 47.3% heat transfer enhancement with only 18.6% pressure drop penalty, resulting in a superior performance ratio of 1.425. The systematic testing across multiple configurations and operating conditions provides comprehensive performance data valuable for industrial heat exchanger design optimization. The results confirm that careful selection and integration of enhancement techniques can overcome the performance plateaus encountered with conventional heat transfer augmentation methods. Future research should address long-term stability, fouling characteristics, and economic viability of nanofluid implementation in large-scale industrial systems to facilitate practical deployment of these promising technologies.

8. References

1 Bahiraei, M., & Hangi, M. (2015). Flow and heat transfer characteristics of magnetic nanofluids: A review. *Journal of Magnetism and Magnetic Materials*, 374, 125-138. https://doi.org/10.1016/j.jmmm.2014.08.004
2 Choi, S. U., & Eastman, J. A. (1995). Enhancing thermal conductivity of fluids with nanoparticles. *ASME International Mechanical Engineering Congress and Exposition*, 66, 99-105.
3 Das, S. K., Putra, N., Thiesen, P., & Roetzel, W. (2003). Temperature dependence of thermal conductivity enhancement for nanofluids. *Journal of Heat Transfer*, 125(4), 567-574. https://doi.org/10.1115/1.1571080

4 Hamilton, R. L., & Crosser, O. K. (1962). Thermal conductivity of heterogeneous two-component systems. *Industrial & Engineering Chemistry Fundamentals*, 1(3), 187-191. https://doi.org/10.1021/i160003a005

5 Kumar, V., Tiwari, A. K., & Ghosh, S. K. (2015). Application of nanofluids in plate heat exchanger: A review. *Energy Conversion and Management*, 105, 1017-1036. https://doi.org/10.1016/j.enconman.2015.08.053

6 Ligrani, P. M., Oliveira, M. M., & Blaskovich, T. (2003). Comparison of heat transfer augmentation techniques. *AIAA Journal*, 41(3), 337-362. https://doi.org/10.2514/2.1964

7 Pantzali, M. N., Mouza, A. A., & Paras, S. V. (2009). Investigating the efficacy of nanofluids as coolants in plate heat exchangers. *Chemical Engineering Science*, 64(14), 3290-3300. https://doi.org/10.1016/j.ces.2009.04.004

8 Selvakumar, P., & Suresh, S. (2012). Convective performance of CuO/water nanofluid in an electronic heat sink. *Experimental Thermal and Fluid Science*, 40, 57-63. https://doi.org/10.1016/j.expthermflusci.2012.01.033

9 Tuckerman, D. B., & Pease, R. F. W. (1981). High-performance heat sinking for VLSI. *IEEE Electron Device Letters*, 2(5), 126-129. https://doi.org/10.1109/EDL.1981.25367

10 Wang, X. Q., & Mujumdar, A. S. (2007). Heat transfer characteristics of nanofluids: A review. *International Journal of Thermal Sciences*, 46(1), 1-19. https://doi.org/10.1016/j.ijthermalsci.2006.06.010

11 Webb, R. L., & Kim, N. H. (2005). *Principles of Enhanced Heat Transfer* (2nd ed.). Taylor & Francis.

12 Wen, D., & Ding, Y. (2004). Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions. *International Journal of Heat and Mass Transfer*, 47(24), 5181-5188. https://doi.org/10.1016/j.ijheatmasstransfer.2004.07.012

13 Xuan, Y., & Li, Q. (2003). Investigation on convective heat transfer and flow features of nanofluids. *Journal of Heat Transfer*, 125(1), 151-155. https://doi.org/10.1115/1.1532008

14 Yu, W., France, D. M., Routbort, J. L., & Choi, S. U. (2008). Review and comparison of nanofluid thermal conductivity and heat transfer enhancements. *Heat Transfer Engineering*, 29(5), 432-460. https://doi.org/10.1080/01457630701850851

15 Bianco, V., Chiacchio, F., Manca, O., & Nardini, S. (2009). Numerical investigation of nanofluids forced convection in circular tubes. *Applied Thermal Engineering*, 29(17-18), 3632-3642.

16 Buongiorno, J. (2006). Convective transport in nanofluids. *Journal of Heat Transfer*, 128(3), 240-250. https://doi.org/10.1115/1.2150834

17 Godson, L., Raja, B., Lal, D. M., & Wongwises, S. (2010). Enhancement of heat transfer using nanofluids—An overview. *Renewable and Sustainable Energy Reviews*, 14(2), 629-641. https://doi.org/10.1016/j.rser.2009.10.004

18 Kakaç, S., & Pramuanjaroenkij, A. (2009). Review of convective heat transfer enhancement with nanofluids. *International Journal of Heat and Mass Transfer*, 52(13-14), 3187-3196. https://doi.org/10.1016/j.ijheatmasstransfer.2009.02.006

19 Pak, B. C., & Cho, Y. I. (1998). Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles. *Experimental Heat Transfer*, 11(2), 151-170. https://doi.org/10.1080/08916159808946559

20 Vajjha, R. S., & Das, D. K. (2009). Experimental determination of thermal conductivity of three nanofluids and development of new correlations. *International Journal of Heat and Mass Transfer*, 52(21-22), 4675-4682. https://doi.org/10.1016/j.ijheatmasstransfer.2009.06.027