氧化铜形貌对纳米流体强化传热性能的影响

朱大海^{1,2}, 于伟^{2*}, 朱桂华^{1,2}, 张迎春², 谢华清^{2*}

1. 东华大学环境科学与工程学院, 上海 201620;

2. 上海第二工业大学工学部环境与材料工程学院, 上海 201209

* 联系人, E-mail: yuwei@sspu.edu.cn; hqxie@sspu.edu.cn

2019-08-09 收稿, 2019-09-20 修回, 2019-09-23 接受, 2019-11-22 网络版发表

国家自然科学基金(51876112, 51590902)、上海市自然科学基金(17ZR1411000)、上海市教育委员会和上海市教育发展基金会基金(15SG52)资助

摘要 纳米流体作为一种提高传热性能的理想工质, 在过去20年中得到了广泛的关注和研究. 我们合成了4种形貌的氧化铜(纳米球、纳米花、纳米棒和纳米线), 并通过两步法制备了氧化铜(CuO)-二甲硅油纳米流体, 从实验和理论两方面探索了CuO形貌对纳米流体强化传热性能的影响. 结果表明, 纳米流体的热导率随CuO体积分数的增加近似线性增加, 和CuO的长径比呈正向关系. 将实验结果与经典的理论预测模型进行比较, 结果较为吻合. 此外, 分析了CuO纳米流体的传热机理. 研究发现, 在纳米流体中, CuO纳米棒和纳米线较高的长径比有利于增加彼此接触的概率, 为热载流子传输找到一条实现最少能量损耗的最佳路径, 构建了一个更快的导热传输网络.

关键词 纳米流体, 热导率, 传热机理, 强化传热, 氧化铜

“纳米流体”的概念是由Choi和Eastman^[1]在1995年提出的. 纳米流体是指将纳米颗粒按一定比例混合在基液中, 制备成稳定的、均匀分散的溶液(悬浮液)系统. 基质通常由金属、非金属氧化物、碳材料等组成, 基液包括水、醇、油等. 在过去的二十多年里, 纳米流体因在换热系统中提高了热交换效率等优异性能而备受关注^[2]. 纳米流体能够强化传热的原因主要体现在两个方面^[3]: (1) 在基液中添加高导热的纳米粒子, 能够显著增大整个体系的热导率, 使传热增强; (2) 纳米粒子的大比表面积和小尺寸效应增大了溶液、颗粒和管壁之间相互接触碰撞的概率, 加剧了布朗运动, 有利于整个体系保持稳定悬浮状态.

金属粒子虽然具有很大的热导率, 但大部分较为昂贵(Au, Ag等), 且在流体中很难稳定存在, 因此一般选择金属氧化物作为纳米流体基质增强传热性能. 相

比于非金属氧化物, 金属氧化物纳米流体具有更大的热导率, 且更容易实现高稳定、低成本的制备^[4]. 金属氧化物(如CuO, Al₂O₃, MgO和ZnO等)在增强纳米流体传热方面应用广泛, 并在某些领域中显示出重要潜力. 其中, CuO具有较高的热导率, 其优秀的光、电、磁、催化等特性在催化、传热等领域的科学研究和应用方面引起了广泛关注^[5]. 当它作为纳米流体添加剂使用时, 可实现纳米流体系统的强化传热增强作用^[6~8]. Javed等人^[9]以棕榈油为基液制备的新型CuO纳米流体表现出优异的强化传热性能, 与纯棕榈油相比, 含0.7 wt% CuO纳米流体的热导率提高了190%. Agarwal等人^[10]研究了水、乙二醇和机油3种不同基液的CuO纳米流体在体积分数为0~2%、温度为10~70℃条件下的热导率. 结果显示, 水、乙二醇和机油基纳米流体最大热导率分别提升40%, 27%, 19%. Nemade和Waghu-

引用格式: 朱大海, 于伟, 朱桂华, 等. 氧化铜形貌对纳米流体强化传热性能的影响. 科学通报, 2020, 65: 222~228

Zhu D H, Yu W, Zhu G H, et al. Influence of copper oxide with different morphologies on heat transfer performance of nanofluids (in Chinese). Chin Sci Bull, 2020, 65: 222~228, doi: 10.1360/TB-2019-0389

ley^[11]研究发现, 超声具有显著增强CuO纳米流体导热性能的作用. 经过60 min超声, CuO纳米流体热导率相比基液提高了18%.

很多研究都表明, CuO纳米粒子作为纳米流体添加剂能够增强传热性能. 然而, 由于制备工艺及体系的不同, 很少有人探究在相同条件下CuO形貌对纳米流体强化传热的影响. 为了验证氧化铜形貌对纳米流体热导率的影响, 制备了CuO纳米球、CuO纳米花、CuO纳米棒、CuO纳米线-二甲基硅油纳米流体, 研究了颗粒体积分数、形状等对热导率的影响, 同时对其强化传热机理和理论预测模型进行了较为深入的分析.

1 实验部分

(i) CuO纳米球的制备. CuO纳米球采用Jia等人^[12]的方法合成. 首先, 将尿素(0.015 M)(1 M=1 mol/L)和醋酸铜溶液(0.015 M)混合, 并将其放入聚四氟乙烯衬里的水热高压釜中. 然后, 将反应釜放入烘箱中并在120°C条件下反应5 h; 冷却至室温, 得到黑色沉淀. 最后, 用去离子水和无水乙醇洗涤数次, 将所得固体颗粒在80°C烘箱中干燥12 h.

(ii) CuO纳米花的制备^[13]. 首先, 将氢氧化钠(10 mL, 1 M)溶液加入硝酸铜(20 mL, 1 M)溶液中; 在磁力搅拌条件下将3.0 g六次甲基四胺加入上述混合液中搅拌均匀. 然后, 加入40 mL的无水乙醇继续搅拌10 min; 将搅拌后的混合溶液放入聚四氟乙烯衬里的水热高压釜中, 反应釜放入烘箱中并在120°C下反应15 h. 最终产物用去离子水和无水乙醇各洗涤2次, 并在60°C烘箱中干燥12 h.

(iii) CuO纳米棒的制备. 称取4.65 g硝酸铜加入102 g去离子水中充分溶解, 再称取26.97 g乙二醇和2.64 g水合肼, 并将上述溶液依次倒入配好的氢氧化钠溶液(2 L, 30 M)中, 在80°C的水浴环境下搅拌1 h. 将产物用去离子水洗涤数次, 并在80°C烘箱中干燥24 h.

(iv) CuO纳米线的制备^[14,15]. CuO纳米线采用改进的Li等人^[14]的方法合成. 首先, 将纯铜箔在稀盐酸溶液(1 M)中浸泡4 h, 用去离子水反复清洗直至清洗液为中性. 然后将铜箔卷曲在管式炉中, 在空气气氛下加热到400°C反应6 h, 加热速率为3°C/min. 最后, 将黑色氧化物从铜箔表面剥落, 所得黑色氧化物即为CuO纳米线.

(v) CuO纳米流体的制备. 采用“两步法”制备不同形貌CuO-二甲基硅油纳米流体. 首先, 将制备的纳米CuO分别加入相同体积的二甲基硅油中. 其次, 搅拌、

超声分散获得稳定、均匀分散的纳米流体.

(vi) 表征方法. 使用扫描电子显微镜(scanning electron microscope, SEM)观察CuO纳米球、CuO纳米花、CuO纳米棒、CuO纳米线的形貌结构. 使用X射线衍射仪(X-ray diffraction, XRD)分析各种形貌CuO的相组成和结晶度, XRD图谱扫描范围为10°~80°(2 θ), 扫描步长为0.01. 使用TciTM/C-Therm热导率测试仪测量分析纳米流体的热导率. 实验系统的温度控制在25°C. 对所有样品进行5次测试以获得平均值.

2 结果与讨论

2.1 CuO纳米粒子的形貌结构表征

至今, 人们合成了各种形貌和结构的CuO纳米粒子和CuO复合材料, 如纳米线、纳米块、纳米球等. CuO因具有良好的热物理性能, 通常被用作添加剂填料以改善不同基液的强化传热性能. 对纳米流体基液的传统研究主要集中在水、乙二醇. 然而, 水、乙二醇的沸点很低, 不能应用于较高温度, 且容易引起器件的磨损和腐蚀, 限制了其在工业生产中的广泛应用^[16]. 相比于水和乙二醇, 二甲基硅油具有热稳定性好、无毒、无味、可循环利用、在-20~180°C范围内可以稳定使用的优点, 是一种理想的基液. 但二甲基硅油的导热系数太低, 意味着较低的强化传热效率, 因此研究者试图通过各种方法来提升其导热性能. 实验研究表明, 在二甲基硅油中添加高导热系数的金属氧化物纳米颗粒能够有效提高二甲基硅油-金属氧化物复合体系纳米流体的强化传热性能^[13,17].

从图1(a), (b)可以看出, 所制备的CuO纳米球分布较为均匀, 直径为400~900 nm. 图1(c), (d)显示典型的花状结构, CuO纳米花是由小的纳米片堆叠组成的近似球体, 平均直径约为2.5 μ m. 图1(e), (f)显示合成后的CuO纳米棒, 直径为150~350 nm, 长度为2.5~7 μ m, 平均长度和平均直径分别为5 μ m和200 nm, 长径比为25. 图1(g), (h)显示合成后的CuO纳米线, 直径为30~80 nm, 长度为3.5~5.5 μ m, 平均长度和平均直径分别为2.79 μ m和39.12 nm, 长径比为71.32.

图2为CuO的XRD图. 可以看出, 4个样品的主要特征衍射峰是一致的, 表明不同形貌的CuO具有相同的相组成. 与氧化铜标准图谱(PDF # 48-1548)的峰值对比, 得到如下结果: 32.6°(110峰); 35.7°(002峰); 38.9°(111峰); 49.0°(-202峰); 53.6°(020峰); 61.7°(-113峰);

图1 CuO纳米球^[17] ((a), (b)), CuO纳米花((c), (d)), CuO纳米棒((e), (f)), 和CuO纳米线^[15] ((g), (h))的SEM图
Figure 1 SEM images of CuO nanospheres ((a), (b)), CuO nanoflowers ((c), (d)), CuO nanobars ((e), (f)), and CuO nanowires ((g), (h))

66.2°(-311峰); 68.4°(220峰). 9个峰位对应一致, 且没有杂峰, 表明样品为纯CuO形式, 没有杂质存在.

2.2 CuO纳米流体的导热系数

从图3可以看出, 随着体积分数增加, CuO纳米流体的热导率呈近似线性关系增加. 在0.75%体积分数

下, CuO纳米球^[17]、CuO纳米花、CuO纳米棒和CuO纳米线^[15]纳米流体的热导率分别为0.155, 0.168, 0.189和0.233 W/(m K), 对应的热导率分别提高了7.00%, 16.11%, 51.62%和60.78%. 因此, 在相同条件下, CuO纳米线纳米流体的热导率比CuO纳米球、CuO纳米花、CuO纳米棒纳米流体的热导率高.

图2 CuO的XRD图
Figure 2 XRD patterns of CuO

前期的研究表明, 纳米流体的导热性取决于许多因素, 例如纳米粒子的性质(大小、形状、浓度、分散性和表面电荷)、基液和温度等^[18]。基液的影响包括基液的性质和黏度的影响。为了解释纳米流体导热系数增加的原因, 许多研究者提出了纳米流体的传热机理, 例如布朗运动^[19]、粒子-流体界面分层^[20]和粒子聚集效应^[21]等。然而, 没有一种通用的机理来解释纳米流体复合体系可以有效强化传热的原因。我们认为纳米材料的结构和形貌对纳米流体的导热性能有重要影响。在相同条件下, CuO纳米流体的热导率和CuO的长径比呈正向关系。这是因为固体颗粒的导热系数远大于液体的导热系数, 当CuO加入到基液中时, 固体颗粒会改变混合体系流体的结构, 热量主要通过高热导率的相转移, 能量传递过程变快, 因此纳米流体热导率增加。CuO纳米球是零维(0-D)纳米材料, CuO纳米花可近

似看作零维的纳米材料, CuO纳米棒和纳米线是一维(1-D)纳米材料。与零维的纳米球相比, 一维的CuO纳米棒和纳米线具有较长的声子平均自由程。另外, 在纳米流体中, CuO纳米棒和纳米线较大的长径比有利于增加彼此接触的概率, 为热载流子传输找到一条实现最少能量损耗的最佳路径, 构建了一个更快的导热传输网络。对于CuO纳米线和纳米棒, CuO纳米线具有比纳米棒更高的长径比。对于CuO纳米球和纳米花, 虽然CuO纳米球具有比CuO纳米花更小的尺寸, 但CuO纳米花具有更大的比表面积, 超出了尺寸效应对纳米流体热传输的影响。所以在本实验中, 相同体积分数下, CuO热导率的关系呈现出CuO纳米球<CuO纳米花<CuO纳米棒<CuO纳米线, 纳米颗粒的形貌对纳米流体的导热性能有重要影响。

2.3 热导率的理论模型

有效的理论模型对预测和指导实验结果具有重要作用。研究者已经提出了许多不同类型的热传导模型来预测纳米流体的热导率。根据传热机理的不同, 热传导模型可分为经典有效介质理论模型、纳米粒子-流体界面分层模型、布朗运动模型、聚集模型和其他机理模型^[22]。我们将不同形貌CuO纳米流体热导率的实验结果与Maxwell^[23], Jeffrey^[24], Bruggeman^[25], Looyenga^[26], Murshed等人^[27], Hamilton和Crosser^[28], Yamada和Ota^[29]几种适用的理论预测模型结果进行比较和讨论, 见表1。

从图4可以看出, Maxwell, Jeffrey, Bruggeman和Looyenga模型的预测值与CuO纳米球的实验结果基本一致(k_b 和 k_p ^[30]分别为0.145和69 W/(m K))。因此, 对于

图3 不同CuO形貌纳米流体热导率(a)和热导率提升率(b)与氧化铜体积分数的关系
Figure 3 Thermal conductivity (a) and enhanced thermal conductivity (b) of nanofluids with different CuO particles as a function of the volume fraction

表1 典型的纳米流体热导率预测模型

Table 1 Typical prediction models about thermal conductivity of nanofluids

研究者	预测模型	重要参数或条件
Maxwell ^[23]	$k_c = k_b \left[\frac{k_p + 2k_b + 2V(k_p - k_b)}{k_p + 2k_b - V(k_p - k_b)} \right]$	早期经典适用于球形纳米粒子预测
Jeffrey ^[24]	$k_c = \left[1 + 3\beta V + V^2 \left(3\beta^2 + \frac{3\beta^2}{4} + \frac{9\beta^2}{16} \frac{x+2}{2x+3} + \frac{3\beta^4}{2^6} + \dots \right) \right] k_b$	$x = \frac{k_p}{k_b}, \beta = \frac{k_p - k_b}{k_p + 2k_b} = \frac{x-1}{x+2},$ 考虑粒子间相互作用, 粒子均匀排列
Bruggeman ^[25]	$k_c = \frac{k_b}{4} \left[(3V-1) \left(\frac{k_p}{k_b} \right) + (2-3V) + \sqrt{\Delta} \right]$	$\Delta = \left[(3V-1)^2 \left(\frac{k_p}{k_b} \right)^2 + (2-3V)^2 + 2(2+9V-9V^2) \frac{k_p}{k_b} \right],$ 考虑粒子间相互作用
Looyenga ^[26]	$k_c = \left[1 - V + V \left(\frac{k_p}{k_b} \right)^{1/3} \right]^3 k_b$	重新考虑了Bruggeman方程和BSttcher关于均匀系统介电常数方程的理论模型
Murshed等人 ^[27]	$k_c = \frac{k_b \left[1 + 0.27V^{4/3} \left(\frac{k_p}{k_b} - 1 \right) \right] \left[1 + \frac{0.52V}{1-V^{1/3}} \left(\frac{k_p}{k_b} - 1 \right) \right]}{1 + V^{4/3} \left(\frac{k_p}{k_b} - 1 \right) \left[\frac{0.52V}{1-V^{1/3}} + 0.27V^{4/3} + 0.27 \right]}$	考虑纳米粒子热阻
Hamilton和Crosser ^[28]	$k_c = k_b \left[\frac{k_p + (n-1)k_b + (n-1)V(k_p - k_b)}{k_p + (n-1)k_b - V(k_p - k_b)} \right]$	适用于预测颗粒的热导率与基础液的导热系数之比大于100的情形; 不规则形状的纳米粒子
Yamada和Ota ^[29]	$k_c = k_b \left[\frac{k_p + Kk_b + KV(k_p - k_b)}{k_p + Kk_b - V(k_p - k_b)} \right]$	$K=2\Phi^{0.2}(l_p/l_d)=(n-1), n=3/\Phi,$ Hamilton-Crosser的修饰, 考虑不规则颗粒几何形状

图4 理论模型和实验数据的分析

Figure 4 Analysis of prediction model and experimental data

零维的规则纳米球, Maxwell, Jeffrey, Bruggeman和Looyenga模型可以满足预测要求。CuO纳米花的实验值比理论预测值稍大, 这是CuO纳米花形貌的近似计

算的结果。还可以看出, Murshed模型的预测值与实验数值偏差较大, 不适合预测CuO纳米流体的热导率。此外, Hamilton-Crosser模型的预测值比纳米线、纳米棒的实验值稍小, 这是由于Hamilton-Crosser模型虽然考虑了形状因子的存在, 但忽略了如温度和团聚等其他因素的影响。当用Hamilton-Crosser模型计算形状因子 $n=3$ 的均匀规则球形纳米颗粒时, Hamilton-Crosser模型与Maxwell模型等价, 所以Hamilton-Crosser模型能较好地预测各种CuO纳米流体的热导率。

3 结论

我们制备了CuO纳米球、CuO纳米花、CuO纳米棒、CuO纳米线-二甲基硅油体系纳米流体, 实验结果表明, 不同形貌的CuO对纳米流体的传热性能具有很大影响。CuO纳米流体热导率随着CuO体积分数的增加而增加, 呈近似线性变化。CuO纳米流体的热导率和

长径比呈正向关系。在纳米流体中,一维的CuO纳米棒和纳米线较大的长径比有利于增加彼此接触的概率,为热载流子传输找到一条实现最少能量损耗的最优路径,构建了一个更快的导热传输网络。通过将实验结果

与经典的理论预测模型进行比较,发现Maxwell, Jeffrey, Bruggeman和Looyenga模型可以满足球形CuO纳米流体热导率的预测要求,Hamilton-Crosser模型能较好地预测各种形貌CuO纳米流体的热导率。

参考文献

- Choi S U S, Eastman J A. Enhancing thermal conductivity of fluids with nanoparticles. *Asme Fed*, 1995, 231: 99–106
- Girishkumar G, Nataraj S. Experimental investigation of copper oxide (CuO) nanofluid on cylindrical heat pipe thermal performance. *Int Res J Eng Technol*, 2016, 33: 125–128
- Ahmadi M H, Mirlohi A, Alhuyi Nazari M, et al. A review of thermal conductivity of various nanofluids. *J Mol Liquids*, 2018, 265: 181–188
- Ramezanizadeh M, Alhuyi Nazari M, Ahmadi M H, et al. Application of nanofluids in thermosyphons: A review. *J Mol Liquids*, 2018, 272: 395–402
- Khurana D, Choudhary R, Subudhi S. A critical review of forced convection heat transfer and pressure drop of Al_2O_3 , TiO_2 and CuO nanofluids. *Heat Mass Transfer*, 2016, 53: 1–19
- Nazari S, Toghraie D. Numerical simulation of heat transfer and fluid flow of water-CuO nanofluid in a sinusoidal channel with a porous medium. *Phys E-Low-dimensional Syst NanoStruct*, 2017, 87: 134–140
- Zhu H T, Zhang C Y, Tang Y M, et al. Novel synthesis and thermal conductivity of CuO nanofluid. *J Phys Chem C*, 2007, 111: 1646–1650
- Karami M, Akhavan-Behabadi M A, Raisee Dehkordi M, et al. Thermo-optical properties of copper oxide nanofluids for direct absorption of solar radiation. *Sol Energy Mater Sol Cells*, 2016, 144: 136–142
- Javed M, Shaik A H, Khan T A, et al. Synthesis of stable waste palm oil based CuO nanofluid for heat transfer applications. *Heat Mass Transfer*, 2018, 54: 1–7
- Agarwal R, Verma K, Agrawal N K, et al. Synthesis, characterization, thermal conductivity and sensitivity of CuO nanofluids. *Appl Thermal Eng*, 2016, 102: 1024–1036
- Nemade K, Waghuley S. A novel approach for enhancement of thermal conductivity of CuO/ H_2O based nanofluids. *Appl Thermal Eng*, 2016, 95: 271–274
- Jia W, Reitz E, Shimpi P, et al. Spherical CuO synthesized by a simple hydrothermal reaction: Concentration-dependent size and its electrocatalytic application. *Mater Res Bull*, 2009, 44: 1681–1686
- Yang H, Liu Z H. Preparation and properties of flower-like copper oxide nanostructures (in Chinese). *J Shanxi Normal Univ: Nat Sci Ed*, 2009, 37: 66–68 [杨慧, 刘志宏. 花状氧化铜纳米结构的制备及其性能研究. 陕西师范大学学报: 自然科学版, 2009, 37: 66–68]
- Li A, Song H, Wan W, et al. Copper oxide nanowire arrays synthesized by *in-situ* thermal oxidation as an anode material for lithium-ion batteries. *Electrochim Acta*, 2014, 132: 42–48
- Zhu D, Wang L, Yu W, et al. Intriguingly high thermal conductivity increment for CuO nanowires contained nanofluids with low viscosity. *Sci Rep*, 2018, 8: 5282
- Mahian O, Kianifar A, Kalogirou S A, et al. A review of the applications of nanofluids in solar energy. *Int J Heat Mass Transfer*, 2013, 57: 582–594
- Yu W, Zhao J, Wang M, et al. Thermal conductivity enhancement in thermal grease containing different CuO structures. *Nanoscale Res Lett*, 2015, 10: 1–8
- Yang X, Liang C, Ma T, et al. A review on thermally conductive polymeric composites: Classification, measurement, model and equations, mechanism and fabrication methods. *Adv Compos Hybrid Mater*, 2018, 1: 207–230
- Xie H, Wang J, Xi T, et al. Dependence of the thermal conductivity of nanoparticle-fluid mixture on the base fluid. *J Mater Sci Lett*, 2002, 21: 1469–1471
- Yu W, France D M, Singh D, et al. Mechanisms and models of effective thermal conductivities of nanofluids. *J Nanosci Nanotech*, 2010, 10: 4824–4849
- Kablinski P, Phillpot S R, Choi S U S, et al. Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids). *Int J Heat Mass Transfer*, 2002, 45: 855–863
- Lee J H, Lee S H, Choi C, et al. A review of thermal conductivity data, mechanisms and models for nanofluids. *Int J Micro-Nano Scale Transp*, 2010, 1: 269–322
- Maxwell J C. A Treatise on electricity and magnetism. *Nature*, 1954, 7: 478–480
- Jeffrey D J. Conduction through a random suspension of spheres. *Proc R Soc A-Math Phys Eng Sci*, 1973, 335: 355–367
- Bruggeman D A G. The calculation of various physical constants of heterogeneous substances. I. The dielectric constants and conductivities of mixtures composed of isotropic substances. *Ann Phys*, 1935, 416: 636–791
- Looyenga H. Dielectric constants of heterogeneous mixtures. *Physica*, 1965, 31: 401–406
- Murshed S M S, Leong K C, Yang C. A model for predicting the effective thermal conductivity of nanoparticle-fluid suspensions. *Int J Nanosci*, 2006, 5: 23–33
- Hamilton R L, Crosser O K. Thermal conductivity of heterogeneous two-component systems. *Ind Eng Chem Fund*, 1962, 1: 187–191
- Yamada E, Ota T. Effective thermal conductivity of dispersed materials. *Wärme Stoffübertr*, 1980, 13: 27–37
- Xue Q, Xu W M. A model of thermal conductivity of nanofluids with interfacial shells. *Mater Chem Phys*, 2005, 90: 298–301

Summary for “氧化铜形貌对纳米流体强化传热性能的影响”

Influence of copper oxide with different morphologies on heat transfer performance of nanofluids

Dahai Zhu^{1,2}, Wei Yu^{2*}, Guihua Zhu^{1,2}, Yingchun Zhang² & Huaqing Xie^{2*}

¹ School of Environmental Science and Engineering, Donghua University, Shanghai 201620, China;

² School of Environmental and Materials Engineering, College of Engineering, Shanghai Polytechnic University, Shanghai 201209, China

* Corresponding authors, E-mail: yuwei@sspu.edu.cn; hqxie@sspu.edu.cn

By acting as an ideal working fluid for the improvement of the heat transfer performance, nanofluids can enhance the process of convective heat transfer by adding nanoparticles to working fluids. As nanofluids can significantly improve heat exchange efficiency in the heat exchange systems, they have been studied extensively as a primary research topic in the past two decades. Owing to its good thermophysical properties, CuO is usually used as additive filler for improving the enhanced heat transfer performance of different base fluids. So far, various morphologies and structures of CuO nanoparticles and CuO composites (such as nanowires, nanoblocks, and nanospheres) have been synthesized. However, due to different preparation processes and systems, very few studies have explored the effect of CuO morphology on the enhanced heat transfer of nanofluids under the same conditions. In fact, the study of the influence of nanoparticle morphology and subsequent mechanism is significant for the promotion of its practical applications. Water and ethylene glycol have been the primary focus of traditional research works conducted on the base fluid of nanofluids. However, water and ethylene glycol have low boiling points; therefore, they cannot be exposed to higher temperatures. This limitation causes the devices (used for water and ethylene glycol) to become more prone to wear and corrosion, thereby limiting the wide applications of water and ethylene glycol in industrial production. As compared to water and ethylene glycol, dimethicone has the following advantages: Good thermal stability, non-toxicity, odorlessness, and recyclability. However, the thermal conductivity of dimethicone is too low, thereby leading to lower heat transfer efficiency. Therefore, researchers have tried to increase its thermal conductivity by employing various methods. Experimental studies have shown that the heat transfer performance of nanofluids can be enhanced by the addition of metal oxide nanoparticles having high thermal conductivity.

In this study, we prepared CuO nanospheres, CuO nanoflowers, CuO nanorods, CuO nanowires-dimethicone nanofluids in order to verify the effect of CuO morphology on the thermal conductivity of nanofluids. The effects of particle volume fraction and shape on thermal conductivity were also studied. In addition, we carried out an in-depth analysis of its enhanced heat transfer mechanism and theoretical prediction model. The experimental results demonstrated that the structure and morphology of nanomaterials have a significant influence on the thermal conductivity of nanofluids. The increase of volume fraction indicates that there is a nearly linear relationship between thermal conductivity and volume fraction. At the volume fraction of 0.75%, thermal conductivities of CuO nanospheres, CuO nanoflowers, CuO nanorods, and CuO nanowires were 0.155, 0.168, 0.189, and 0.233 W/(m K), respectively. The corresponding thermal conductivities also increased by 7.00%, 16.11%, 51.62% and 60.78%, respectively. Through comparison, we conclude that the thermal conductivity of CuO nanofluids is positively correlated with the aspect ratio of CuO under the same conditions.

Through a comprehensive comparison of experimental results and the classical theoretical prediction models, we found out that the Maxwell, Jeffrey, Bruggeman, and Looyenga models can meet the prediction requirements of thermal conductivity of spherical CuO nanofluids. The Hamilton-Crosser model can serve as a better predictor of the thermal conductivity of CuO nanofluids. In addition, we analyzed the heat transfer mechanism of CuO nanofluids. It was found that the higher aspect ratio of CuO nanorods and nanowires helps in increasing the probability of contact with each other. This, in turn, established an optimal condition for the hot carrier transport to achieve a minimum energy loss path, thus building a faster thermal conduction network.

nanofluid, thermal conductivity, heat transfer mechanism, enhanced heat transfer, CuO

doi: [10.1360/TB-2019-0389](https://doi.org/10.1360/TB-2019-0389)