第30卷第2期 2015年3月
热 能 动 力 工 程
JOURNAL OF ENGINEERING FOR THERMAL ENERGY AND POWER
Vol. 30, No. 2 Mar., 2015

文章编号:1001-2060(2015)02-0200-05

$CuO-H_2O$ 纳米流体强化换热的数值模拟

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摘 要:采用数值模拟的方法研究了矩形腔内 $CuO-H_2O$ 纳米流体自然对流的换热特性和换热机理。重点分析了二维封闭腔内不同 Ra 数下,纳米颗粒体积分数和粒径对 $CuO-H_2O$ 纳米流体自然对流时温度场和速度场的影响,并探讨了纳米颗粒布朗运动对换热的影响。数值模拟结果表明:对于给定的 Ra 数,随着体积分数的增大和颗粒粒径的减小,纳米流体的换热效果会显著增强;当 Ra 数较小时,换热形式主要表现为热传导,随着 Ra 数的增大,换热形式逐渐变为以热对流为主;纳米颗粒布朗运动是影响纳米流体换热的重要因素,随着布朗运动的增强,纳米流体内部的能量传递增强,从而使换热增强。

关 键 词:纳米流体;强化换热;布朗运动;数值模拟

中图分类号:TK124 文献标识码:A

DOI:10.16146/j.cnki.rndlgc.2015.02.006

引 言

纳米流体是一种新型高效的换热工质,添加纳米颗粒能够显著增强基液的换热特性[1-6]。文献[7]从纳米流体结构的微观角度出发,通过理论分析和实验验证,认为导致纳米流体换热增强的因素主要有两方面,一方面是纳米颗粒的导热系数远大于基液的导热系数,另一方面是纳米颗粒的微运动强化了基液内部的能量传递。文献[8]从理论上进一步研究了纳米流体强化换热的微观机理,并分析了纳米颗粒布朗运动的影响。除了从实验和理论角度研究其机理外,还有一些学者采用数值模拟的方法对其进行了研究。文献[9]模拟了封闭腔内纳米流体的自然对流,发现纳米颗粒体积分数是影响增强换热效果的主要因素。文献[10]对 $Cu-H_2O$ 纳米流体的自然对流换热特性进行了模拟,重点研究了Cu纳米颗粒的添加量和 Gr 数对换热的影响,并从流函数和速度场分析了增强换热的机理。文献[11]研究了梯形封闭腔内 Al_2O_3-EG 纳米流体的换热特性,分析了封闭腔尺寸比、Ra 数以及纳米颗粒含量对换热的影响,并发现在不考虑布朗运动时,纳米颗粒反而削弱了换热能力,因此在分析纳米流体强化换热时必须考虑纳米颗粒的布朗运动。尽管纳米流体增强换热的机理已经得到了初步的研究,但是不同的学者得到的结论不尽相同,另外,纳米颗粒粒径也是影响纳米流体换热的因素,而大多数学者却没有对此进行研究。

本研究采用数值模拟的方法研究了矩形封闭腔内 $CuO-H_2O$ 纳米流体的自然对流,重点分析了不同Ra数下,体积分数和颗粒粒径对换热的影响,并探讨了纳米颗粒布朗运动对换热的影响。

1 物理模型

采用的物理模型为充满 $CuO-H_2O$ 纳米流体的二维矩形封闭腔,高宽比为1/2,如图1所示。左壁是高温壁,温度为 T_h,右壁是低温壁,温度为 T_c,上下壁面均绝热。假设矩形腔内的 $CuO-H_2O$ 纳米流体是连续介质,纳米颗粒和液体之间处于热平衡状态,并且彼此之间没有发生滑移。

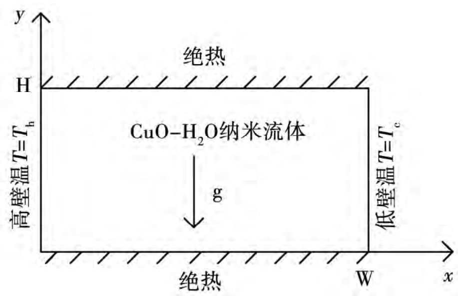

图1 物理模型的示意图

Fig. 1 Schematic diagram of the physical model

对于纳米流体的热物性,除了考虑由浮升力作用导致的密度变化外,其余均视为常数。采用的纳米颗粒粒径为20、60和100 nm,体积分数为5%、

收稿日期:2014-05-23; 修订日期:2014-06-23
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10% 和 15%，纳米流体密度的计算式为:

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_{np} \quad (1)$$

式中: φ —纳米颗粒的体积分数; 下标 nf、f、np—纳米流体、基液和纳米颗粒。

纳米流体的定压比热容 c_p 和热膨胀系数 β 分别为:

$$(\rho c_p)_{nf} = (1-\varphi)(\rho c_p)_f + \varphi(\rho c_p)_{np} \quad (2)$$

$$(\rho\beta)_{nf} = (1-\varphi)(\rho\beta)_f + \varphi(\rho\beta)_{np} \quad (3)$$

纳米流体的有效动力粘度为:

$$\mu_{nf} = \frac{\mu_f}{(1-\varphi)2.5} \quad (4)$$

综合考虑纳米颗粒体积分数和布朗运动对导热系数的影响，由文献[12]可知纳米流体导热系数的计算式为:

$$\frac{k_{nf}}{k_f} = (1+40000Re^{2.4}Pr^{0.333}\varphi)\left[\frac{(1+2\alpha)+2\varphi(1-\alpha)}{(1+2\alpha)-\varphi(1-\alpha)}\right] \quad (5)$$

Re 数和 α 分别表示为:

$$Re = \sqrt{\frac{18KBT}{\pi\rho_{np}\nu_f^2 d_{np}}}, \alpha = k_{np}/k_f$$

式中: kB—波尔兹曼常数，J/K; d_{np}—纳米颗粒粒径，nm; Re 数—作用于流体微团的惯性力与粘性力之比，表征了纳米流体粘性的影响; Pr 数—动量扩散能力与热量扩散能力的相对大小，表征了纳米颗粒布朗运动的影响。

表 1 分别列出了水基液、CuO 纳米颗粒和不同体积分数下 20 nm CuO – H_2O 纳米流体的热物性。

表 1 水基液、CuO 纳米颗粒和 20 nm CuO – H_2O 纳米流体的热物性

Tab. 1 Thermo-physical properties of a water-based solution, CuO nanoparticles and 20 nm CuO – H_2O nanofluid

热物性	H_2O	CuO	体积分数 φ = 0.05	体积分数 φ = 0.10	体积分数 φ = 0.15
密度 ρ/kg·m^{-3}	997.1	6 500	1 272.2	1 547.4	1 822.5
定压比热容 c_p/J·(kg·K)$^{-1}$	4 179	540	3 250	2 650	2 232
导热系数 k/W·(m·K)$^{-1}$	0.613	18	0.658	0.692	0.716
热膨胀系数 β/(K^{-1}) ×10^5	21	0.85	15.85	12.54	10.22
动力粘度 μ/(Pa·s) ×10^3	0.894	–	1.016	1.163	1.342

2 数学模型

采用单相法模拟矩形腔内纳米流体的二维稳态层流自然对流，以无量纲形式表示，其控制方程:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (6)$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \quad (7)$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \left(\frac{Ra}{Pr}\right)\theta \quad (8)$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{Pr}\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \quad (9)$$

式中: U 和 V—水平和竖直方向上的无量纲分速度; P—指无量纲压力; Ra 数—无量纲参数; 用于同时考虑浮升力与黏性力在自然对流中的作用，可判断层流与湍流; θ—指无量纲温差。

这些无量纲参数可分别表示为:

$$X = \frac{x}{H}, Y = \frac{y}{H}, U = \frac{uH}{\nu}, V = \frac{vH}{\nu}, P = \frac{(p+\rho g y)H^2}{\rho\nu^2}, \theta = \frac{T-T_c}{T_h-T_c}, Ra = \frac{g\beta(T_h-T_c)H^3}{\nu a},$$

$$Pr = \frac{\nu}{a}$$

式中: ν —运动粘度; a—热扩散系数，$a = k/(\rho c_p)$。

物理模型的无量纲边界条件如下:

$X = 0$ $U = V = 0$, $\theta = 1$

$X = 2$ $U = V = 0$, $\theta = 0$

$Y = 0,1$ $U = V = \partial\theta/\partial Y = 0$

采用有限体积法求解带有上述边界条件的控制方程，采用 SIMPLE 算法处理压力和速度场的耦合，采用二阶迎风格式处理对流项，采用 Boussinesq 假设来处理由浮升力导致的密度变化。

3 结果与分析

3.1 模型验证

Nu 数是判断换热强弱的重要依据，左壁面局部 Nu 数定义为:

$$Nu = -\left(\frac{k_{nf}}{k_f}\right)\frac{\partial\theta}{\partial X}\bigg|_{X=0} \quad (10)$$

对局部 Nu 数进行积分便可以得到平均 Nu 数，其表示封闭腔内纳米流体总换热能力。平均 Nu 数计算式为:

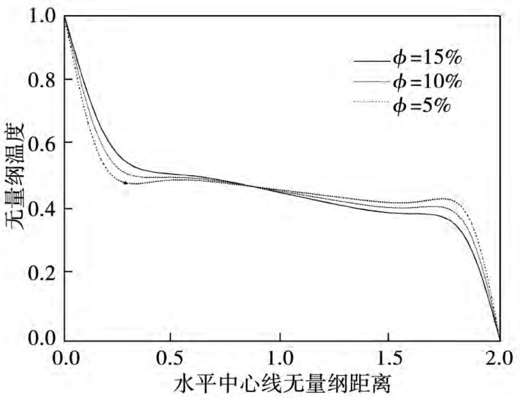
$$Nu_{avg} = \int_0^1 Nu|_{X=0} \mathrm{d}Y \tag{11}$$

为了验证上述模型的正确性，将粒径为 20 nm、体积分数为 5% 的纳米流体在不同 Ra 数下的平均 Nu 数与已有的文献结果进行对比，如表 2 所示，发现采用本模型计算的结果与文献[9]的计算结果相吻合，说明所采用的模型是正确的。

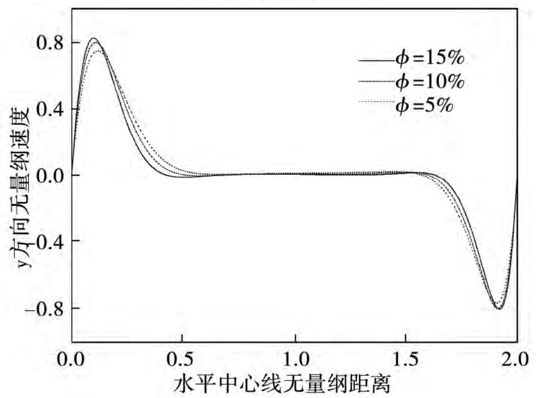
表 2 模拟结果与文献的对比

Tab. 2 Contrast of the simulation results with those given in the literatures

瑞利数	本文	文献[9]
$Ra=10^3$	1.121	1.118
$Ra=10^4$	2.238	2.245
$Ra=10^5$	4.519	4.522



(a) 无量纲温度分布



(b) y方向速度分布

图 2 不同体积分数下温度和 y 方向速度分布

Fig. 2 Distribution of the temperature and velocity in the y direction under various volume fractions

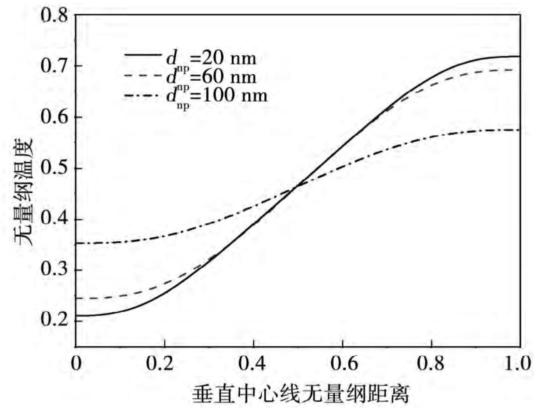
3.2 纳米颗粒体积分数的影响

图 2 为 $Ra=10^3$、$d_{np}=20$ nm 条件下纳米颗粒体积分数对矩形腔水平中心线上温度和 y 方向速度分布的影响规律。

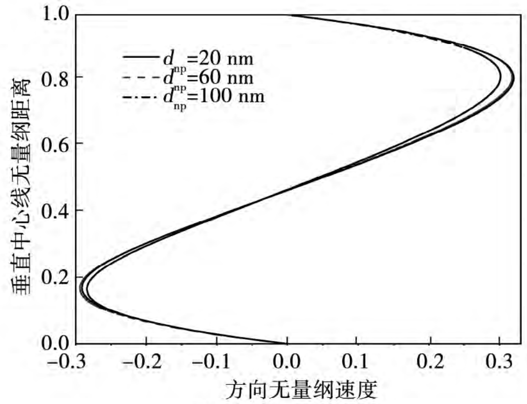
从图 2(a) 中可以看出，随着体积分数的增大，纳米流体的换热特性显著增强。一方面，由式(5)可知纳米流体的有效导热系数随着体积分数的增大而增大; 另一方面，从图 2(b) 中可以看出，随着体积分数的增大，水平中心线上 y 方向速度的峰值变大，这说明纳米颗粒的随机运动增强，使得纳米颗粒和基液之间的相互作用增强，从而导致纳米流体内部热交换率和能量传递作用增强，因此强化了纳米流体的换热特性。

3.3 纳米颗粒粒径的影响

图 3 为 $Ra=10^3$、$\varphi=5\%$ 条件下纳米颗粒粒径对矩形腔垂直中心线上温度和 x 方向速度分布的影响规律。



(a) 温度分布



(b) 方向速度分布

图 3 不同粒径下温度和 x 方向速度分布

Fig. 3 Distribution of the temperature and velocity in the x direction at various particle sizes

从图 3(a) 中可知随着纳米颗粒粒径的减小，纳米流体的换热特性增强。颗粒粒径对纳米流体换热特性的影响是多方面的，由式(5) 可知颗粒粒径的减小可以使纳米流体的有效导热系数增大。纳米颗粒在水基液中做无规则的布朗运动，同时带动着颗粒周围的液体微元做无规则的运动，而颗粒与颗粒之间的液体微元相互作用，形成了局部的微对流，增强了液体内部的混合，因此纳米颗粒布朗运动使得纳米流体内部的热交换率增大，并且布朗运动速率越大，增强换热效果越显著。从微观角度看，纳米颗粒在效果上相当于微型的"搅拌桨"，布朗运动就相当于搅拌作用，使得液体混合更加剧烈。在一定的体积分数下，颗粒粒径越小，颗粒的数目越多，即"搅拌桨"越多，纳米流体内部混合越剧烈，热交换率也越大。另外，从图 3(b) 中可以看出，随着颗粒粒径的减小，垂直中心线上 x 方向速度越大，说明纳米颗粒布朗运动速率越大，则搅拌作用更强，从而使得换热增强作用更大。

3.4　*Ra* 数的影响

图 4 为 $d_{np}=20$ nm、$\varphi=5\%$ 条件下 *Ra* 数对矩形腔内纳米流体流函数和等温线的影响规律。

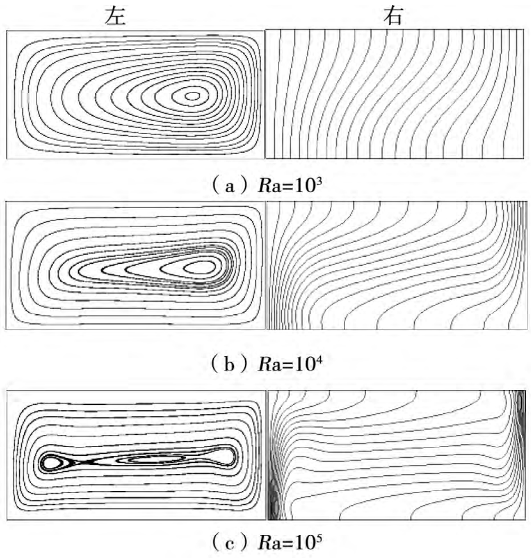


图 4　不同 *Ra* 数下纳米流体的流函数(左) 和等温线(右) 图

Fig. 4 Chart showing stream function (left) and the isotherms (right) of the nanofluid at various *Ra* numbers

从流函数图中可以看出，矩形腔内纳米流体自然对流形成的旋涡随着 *Ra* 数的增大逐渐变大，并且当 *Ra* 数达到一定值时，旋涡会破裂变为多个旋涡，说明矩形腔内换热不断增强。从等温线图中可以看出，当 *Ra* 数较小时，等温线几乎是垂直的，则总的热量是从高温左壁面向低温右壁面按水平方向传递的，说明此时传热是以热传导方式进行的; 随着 *Ra* 数的增大，当它大于某一值后，等温线逐渐变成水平的，但是在冷热壁面附近的薄边界层内仍保持着垂直，这说明此时在冷热壁面附近的薄边界层内的换热仍以热传导形式进行，而在整个矩形腔内的换热却变为以热对流为主。

4　结　论

采用数值模拟的方法研究了矩形腔内 CuO - H_2O 纳米流体的换热特性及换热机理，重点分析了纳米颗粒体积分数、粒径和 *Ra* 数对换热的影响，并详细分析了布朗运动对增强换热的影响，得出主要结论:

(1) 随着纳米颗粒体积分数的增大，纳米流体的有效导热系数增大，并且矩形腔水平中心线上 y 方向速度的峰值增大，使得纳米颗粒和基液之间的相互作用增强，从而导致纳米流体内部热交换率和能量传递作用增强，因此纳米流体的换热特性不断增强。

(2) 纳米颗粒布朗运动带动周围液体做无规则运动，颗粒与颗粒之间的液体相互作用，形成局部的微对流，从而增强液体内部的混合。随着纳米颗粒粒径的减小，其布朗运动越剧烈，局部微对流作用越强，使得纳米流体内部热交换率越大，因此纳米流体的增强换热作用增大。

(3) 随着 *Ra* 数的增大，流函数图中的旋涡逐渐变大，当 *Ra* 数达到一定值后，旋涡破裂为多个小旋涡，说明纳米流体的换热不断增强; 当 *Ra* 数较小时，纳米流体的换热以热传导的方式进行，当 *Ra* 数较大时，换热方式变为以热对流为主。

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（丛　敏　编辑）

新技术、新设计

沙特 2014 年光热发电产业发展未达预期

DOI:10.16146/j.cnki.rndlgc.2015.02.007

沙特规划到 2032 年实现 25GW 的光热发电装机，雄心勃勃。但观察沙特市场 2014 年的表现，并未达人所愿。沙特 2013 年发布了光热发电项目竞争性招标白皮书和可再生能源资源地图集，但今年却未见有实际动作。这可能要归结于沙特的可再生能源行政权利正由 K. A. CARE 向沙特国家石油公司转移，而后者对光热发电的态度有所不同。唯一利好的消息是沙特 SEC 发布了 Duba 1 项目招标函，该项目是一个配 50 MW 光热装机的 ISCC 燃油光热联合循环发电站。这离人们普遍期待的大量光热项目将在今年开始招标相差太远。

（吉桂明　摘译）

lar narrow channel outlet with a cross section of 20 mm × 3 mm, under the condition of the supercooling state in which the pressure was normal and the inlet temperature was 313 K, the ultrasonic attenuation spectrum method was used to measure the gas content and dimension distribution of bubbles in a vertical rising gas-liquid two-phase bubble flow arisen from the boiling of a water flow and analyze the influence of the heating power and the mass flow rate on the gas content, bubble dimensions and their distribution of a bubble flow. The test results show that when the mass flow rate is constant, with an increase of the heating power, the medium diameter of the bubbles D_{50} will increase, the distribution of dimensions will broaden and the gas content of the gas-liquid two-phase flow will also increase. Under the condition of the operating conditions being roughly equivalent (which can be judged from the outlet temperature T_2 and the outlet absolute pressure P_2), with an increase of the mass flow rate, the medium diameter of the bubbles D_{50} will decrease, the distribution of dimensions will narrow and the gas content will decrease. When the gas content measured by using the ultrasonic method is compared with that measured by using the gas-liquid separation method, the maximal relative deviation reaches 4.5%, indicating that the measurement results obtained from the test are basically reliable. **Key Words:** gas content, dimension distribution of bubbles, gas-liquid two-phase flow, supersonic attenuation spectrum, rectangular narrow channel

CuO-H_2O 纳米流体强化换热的数值模拟 = **Numerical Simulation of the Intensified Heat Exchange of CUO-H_2O Nano-fluid** [刊, 汉] SUN Chao-jie, SUN Bao-min, ZHONG Ya-feng, JIANG Jia-zong (Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control, North China University of Electric Power, Beijing, China, Post Code: 102206) //Journal of Engineering for Thermal Energy & Power. -2015, 30(2). -200-204

By using the numerical simulation method, studied were the natural convection-based heat exchange characteristics and of CUO-H_2O nano-fluid inside a rectangular cavity and the mechanism governing the heat exchange. The emphasis was placed on an analysis of the influence of volumetric fraction and particle size of the nano-fluid on the temperature and speed field inside a two-dimensional enclosed cavity at various Ra numbers formed when the CUO-H_2O nano-fluid is undergoing the natural convection and an investigation of the influence of Brownian movement of nano-fluid on the heat exchange. The numerical simulation results show that for a given Ra number, the heat exchange efficiency of the nano-fluid will notably enhance. When Ra number is relatively small, the heat exchange is mainly regarded as the heat conduction. With an increase of Ra number, the heat exchange will gradually become a convection-based heat exchange. Brownian movement of the nano-particles will become an important factor influencing the heat exchange of the nano-fluid. With the enhancement of Brownian movement,the energy transfer inside the nano-fluid will also enhance,thus intensifying the heat exchange. **Key Words:** nanofluid,intensified heat exchange,numerical simulation,Brownian movement

基于内置V型肋片的直通道内流动与传热的数值研究 = Numerical Simulation of the Flow and Heat Transfer in a Straight Channel Installed Inside With V-shaped Ribs［刊,汉］ZHANG Ai-ping,BI Shuai,FU Lei (College of Energy Source and Power,Northeast University of Electric Power,Jilin,China,Post Code: 132012) //Journal of Engineering for Thermal Energy & Power. -2015,30(2). -205 -211

By using the structuralized hexahedral meshes and the K-ε turbulent flow model,the authors sought the solutions to the 3-D N-S equation,the authors sought the solutions to the N-S equation and conducted a numerical simulation of the flow and heat exchange characteristics in a direct cooling channel installed inside with V-shaped flow disturbance ribs at various flow guide angles α when the Reynolds number at the inlet is 20000. On this basis,the influence of the flow guide angle of ribs α on the heat exchange efficiency and flow losses on the wall surfaces between ribs was analyzed and a comprehensive optimization search was conducted. It has been found that the overall heat exchange efficiency and comprehensive cooling efficiency of the direct cooling channel with ribs assume a similar function relationship with the flow guide angle α. When α is 47.25 degrees,the overall heat exchange efficiency of the channel is highest and when α is 31.57 degrees,the comprehensive cooling efficiency of the channel is optimal and when α is 30 degrees,the flow losses in the channel are largest. **Key Words:** gas turbine,inner cooling channel,V-shaped rib,whole-body optimization search

多管式气泡泵设计 = Design of a Multiple Tube Bubble Pump［刊,汉］LU Yin-zhe,LIU Dao-ping,XU Huang-dong (Refrigeration Research Institute,Shanghai University of Science and Technology,Shanghai,China,Post Code: 200093) //Journal of Engineering for Thermal Energy & Power. -2015,30(2). -212 -217

Based on the currently-available experimental and theoretical study of bubble pumps,the authors conducted a thermodynamic calculation. When the tube of a single tube bubble pump is chosen with its maximal diameter being 31 mm,its lifting flow rate is 39.23 g/s. When the amount of the cooling energy consumed by a whole single pressure absorption type refrigeration system is chosen as 3 kW,to obtain an even larger lifting flow rate inside the tube of the bubble pump,the corresponding total flow rate inside the bubble pump will be 42.3 g/s. By using a multiple tube