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两级气泡泵泵起现象的实验研究

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摘 要: 通过搭建实验台, 以水和不同浓度的溴化锂溶液为工质针对两级气泡泵的泵起做了大量实验研究和分析。实验研究表明: 冷剂蒸汽加热是第二级气泡泵泵起的一个因素, 另一个因素是中间溶液降压闪发形成气泡; 两级气泡泵的泵起与中间溶液和一级冷剂蒸汽的压力差有关; 工质为水时, 当一级冷剂蒸汽压力与中间溶液压力之差为 3.5-3.9 kPa 之间时, 两级溶液泵能够运行起来, 且启动时间随着浸没高度的增大而减小; 工质为溴化锂溶液时, 随着溶液浓度的增大, 两级气泡泵泵起所需要的压差是增大的, 且比以水为工质时压差大。启动时间在溴化锂溶液浓度为 45.5%-54% 范围内时随着浓度的增大而增大。在浓度为 54%-59.5% 时, 随着浓度的增大而减小, 在浓度为 54% 时气泡泵的启动时间达到最大值。

关 键 词: 两级气泡泵; 泵起现象; 中间溶液, 吸收式制冷; 压差

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引 言

无泵型溴化锂吸收式制冷循环装置中的动力靠气泡泵提供, 其吸收外部热源(热水或蒸汽) 的热量将溶液提升一定高度。因其不需要高品质的能量, 所以真正实现绿色环保[1-2]。近年来国内外很多学者对单级气泡泵做了大量研究, 包括建立了气泡泵运行的数学模型并搭建单级气泡泵实验台, 对影响气泡泵性能的诸多因素进行实验研究[3-4]。彭一川等人[5]提出了气泡泵的相关理论计算公式, 谷雅秀等人[6-7]在气泡泵制冷循环中使用了二次发生器。但对于两级气泡泵没有太多的研究和实验数据供参考, 尤其对小型两级气泡泵的泵起现象的研究。

两级气泡泵中高压发生器中的溶液直接被驱动热源加热浓缩, 产生一次冷剂蒸汽; 低压发生器中的溶液则被来自高压发生器的一次冷剂蒸汽加热产生气泡, 将溶液进一步提升、浓缩并产生二次冷剂蒸汽。本研究搭建的两级气泡泵实验装置, 通过改变浸没高度等因素来研究泵起现象, 其中一次冷剂蒸汽加热只是第二级气泡泵泵起的一个因素, 还有另一个因素是中间溶液的闪发形成气泡, 并给出了两级气泡泵泵起时一二两级气液分离器的压差, 为以后研究两级气泡泵提供参考。

1 实验装置

实验台主要包括高、低压发生器、一、二两级气液分离器、冷凝器、针阀调压阀以及它们之间相互连通的管路等。系统图如图 1 所示。

此实验台是一套观察无泵型溴化锂吸收式制冷装置中气泡泵提升性能的系统。为了更好地观察各参数对气泡泵提升性能的影响分析, 气泡泵采用两根一米长可视化玻璃管。同时, 为了简化实验装置, 系统中省去了蒸发器等部件。高压发生器内设有电加热棒接口, 加热棒由外部电源通电并提供热量, 实验过程中通过改变加热棒的电压来控制加热功率, 加热功率范围为 0-4 000 W。通过调节吸收器的高度来调节浸没高度, 范围在 300-450 mm 和 450-450 mm(分别为一二两级气泡泵的浸没高度) 之间, 且一级提升高度 1 250 mm, 二级提升高度 1 400 mm 保持不变。工质中溴化锂溶液浓度范围为 45.5%-59.5%。表 1 为实验仪器规格。

表 1 实验仪规格

Tab. 1 Specifications of the instruments used in the test

实验仪器	规格参数
热电偶	T 型, 精度等级为 B, 测量范围 0-800 ℃
压力传感器	US10000 型, 精度为 ±0.1%, 测量范围为 0-34.47 kPa
数据采集仪	FLUKE 2635A, 20 通道

实验在加热功率、浸没高度等参数都确定的条件下观察气泡泵的泵起现象。通过反复实验, 得出了第二级气泡泵泵起的条件——中间溶液与一级冷剂蒸汽的具体压力关系。下面主要针对一、二级所

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泡泵的直径均为 7.7 mm，水和不同浓度溴化锂溶液为工质的两级气泡泵进行分析。

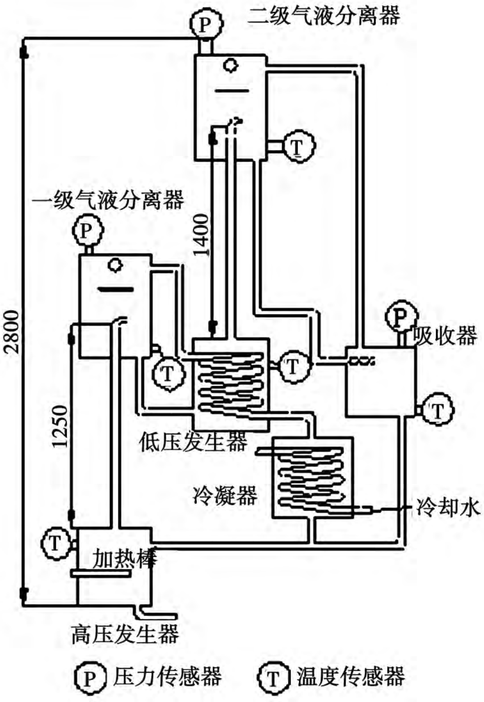

图 1　两级气泡泵实验装置简图(mm)

Fig. 1 Simplified drawing of the dual-stage bubble pump test device(mm)

2　气泡泵工作过程简要分析

高压发生器中溶液被加热器加热后产生气泡。气泡泵中的气液混合物在吸收器与发生器之间的液位差作用下推动气液混合物到达一级气液分离器。其中气体进入低压发生器，换热后进入冷凝器; 中间溶液流入低压发生器，二级气泡泵泵起后，进一步浓缩的溶液经气液分离器分离后进入吸收器喷淋，来吸收二次冷剂蒸汽(经过二级气液分离器分离的水蒸气)。为了提高吸收效果，实验过程中对吸收器进行冷却。理论循环如图 2 所示，高压发生器的压力为 P_r，从吸收器出来的稀溶液流入高压发生器，进口处溶液处于过冷态 2，经过换热后到达 5_H 点开始沸腾产生气泡，使泵侧溶液密度降低，气泡泵开始运行，$2-5_H$ 过程浓度不变，为 W_a。在高压发生器的出口处，溶液被浓缩到状态 4_H 的质量分数为 W_{r0} 的中间溶液。中间溶液经减压阀后进入低压发生器，压力为 P_k。由于压力突降，中间溶液闪发，形成气泡促使第二级气泡泵泵起，溶液闪发吸收热量后变为质量分数为 W_{r1} 的饱和浓溶液，图中为过程 4_H-8_H，同时一级冷剂蒸汽通过低压发生器盘管对溶液进一步加热，从而进一步浓缩至质量分数 W_{r2} 的浓溶液，图中为过程 8_H-4。

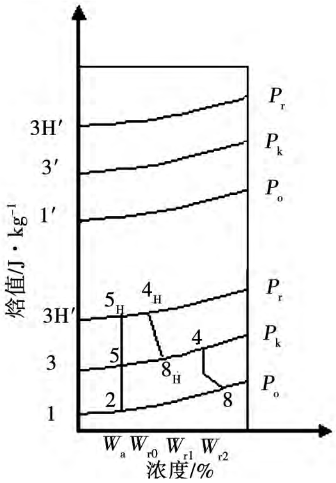

图 2　二级气泡泵循环的焓 - 浓度图

Fig. 2 h-ξ diagram of the dual-stage bubble pump cycle

3　实验结果

3.1　水为工质时实验结果及分析

3.1.1　一、二级气泡泵浸没高度分别为 350 和 450 mm

一、二级气泡泵浸没高度分别为 350 和 450 mm 时，加热功率 3 000 W，一、二级气泡泵管径均为 7.7 mm，提升高度分别为 1 250 mm 和 1 400 mm，实验运行参数如图 3 所示。

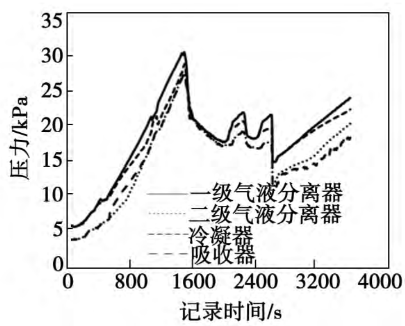

图 3　浸没高度分别为 350 和 450 mm 时压力图

Fig. 3 Pressure diagram when the immerging height ranges from 350 to 450 mm

实验结果表明: 此浸没高度时，两级气泡泵泵起的时间较长。实验最后能够达到较好运行状态，两个气液分离器的压力差为 3.5 - 3.8 kPa。

3.1.2　**一、二级气泡泵浸没高度分别为 400 和 450 mm**

保持加热功率 3 000 W、气泡泵管径及提升高度不变，第一级气泡泵浸没高度升高为 400 mm，第二级气泡泵提升高度保持 450 mm 不变时，运行参数如图 4 所示。

实验数据表明：在此浸没高度下，两级气泡泵最终稳定运行时，一级气液分离器和二级气液分离器的压力的差值趋于稳定，介于 3.6 – 3.8 kPa 之间。

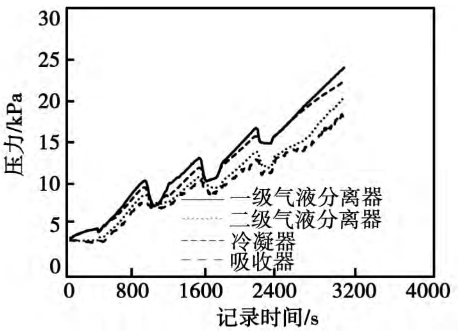

图 4　浸没高度为 400 和 450 mm 时压力图

Fig. 4 Pressure diagram when the immerging height ranges from 400 to 450 mm

3.1.3　**一、二级气泡泵浸没高度均为 450 mm**

两级气泡泵浸没高度均为 450mm，其它条件不变时，各装置运行压力如图 5 所示。

从图 5 中可以看出，气泡泵在运行后期一二两级气液分离器的压差趋于稳定，约为 3.6 – 3.9 kPa。

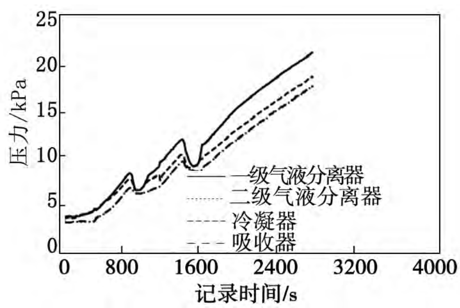

图 5　一、二级气泡泵浸没高度均为 450 mm 时压力图

Fig. 5 Pressure diagram when the immerging height is 450 mm

表 2 所示以水为工质时，不同浸没高度下气泡泵的启动时间。从表 2 中可以看出，随着一级气泡泵浸没高度的提高，气泡泵泵起的时间变短。

表 2　气泡泵启动时间

Tab. 2 The startup time of the bubble pump

浸没高度/mm	350 – 450	400 – 450	450 – 450
启动时间/s	480	220	190

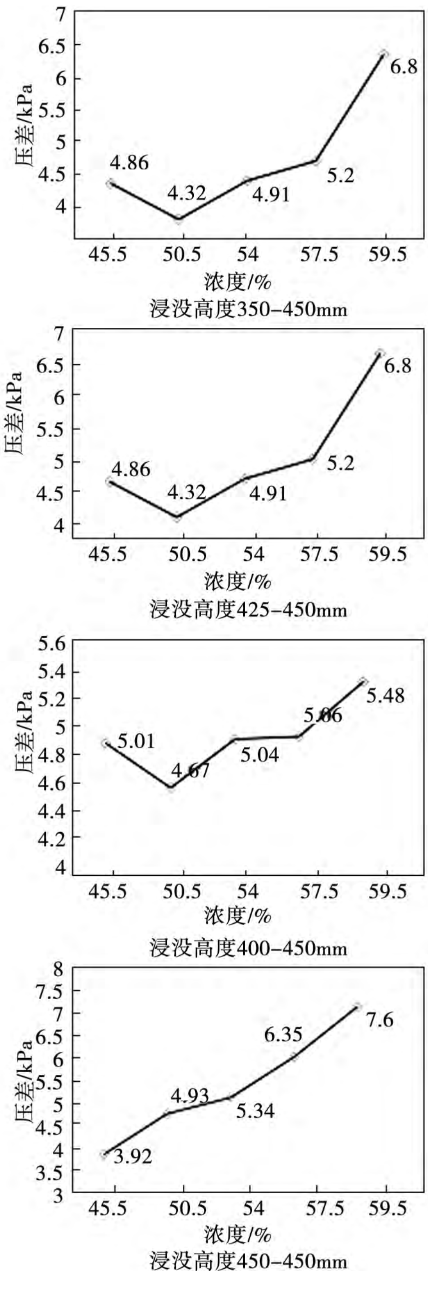

图 6　浓度不同时气泡泵泵起时的压差

Fig. 6 Pressure difference at various concentrations when the bubble pump is starting up

3.2　**溴化锂溶液为工质时气泡泵泵起与一、二两级汽液分离器的压差**

以不同浓度的溴化锂溶液为工质进行实验。实验过程中保持加热功率 1 800 W 和提升高度不变，浸没高度分别为 350 – 450 mm、400 – 450 mm、425 –

450 mm 及 450 − 450 mm。实验数据如图 6 所示。

从图 6 中可以看出,当两级气泡泵泵起时,一二两级气液分离器的压差是随着溶液浓度的增大而增大的,且比以水为工质时压差大。

加热功率 1 800 W,以不同浓度的溴化锂溶液为工质对以上 4 个浸没高度下的气泡泵进行启动时间统计。统计过程中以高压发生器中溶液温度为 38 ℃为零时刻。如图 7 所示。

从图 7 可以看出。在浓度为 45.5% − 54% 时,气泡泵的启动时间随着浓度的增大而增大。在浓度为 54% − 59.5% 时,气泡泵的启动时间基本上随浓度的增大而减小。在浓度为 54% 时,气泡泵的启动时间最长。

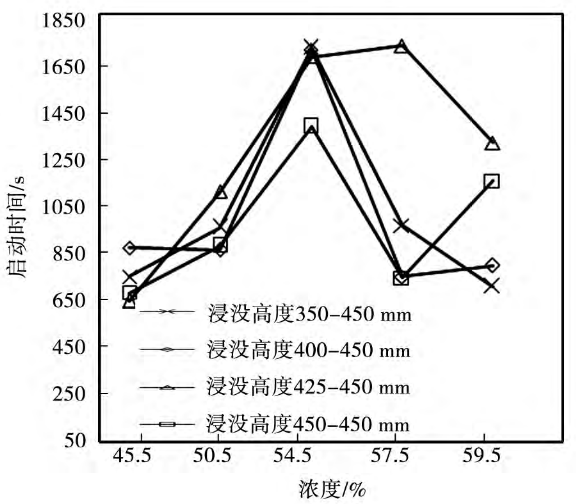

图 7　浓度不同时气泡泵的启动时间

Fig. 7 The startup time of the bubble pump at various concentrations

4　结　论

在加热功率、提升高度、工质和管径保持不变的情况下,一级浸没高度越大,越有利于两级气泡泵的泵起。同时,两级气泡泵泵起与中间溶液的压力有很大关系。实验数据表明,工质为水时,当一级冷剂蒸汽压力与中间溶液压力之差为 3.5 − 3.9 kPa 之间时,两级溶液泵能够运行起来。通过对比各点压力值与饱和水蒸气表,可以得出,第二级气泡泵的泵起因素中中间溶液闪发和一级冷剂蒸汽的加热起重要作用。通过调节两个压力调节阀,最终可以使两级气泡泵泵起并稳定运行起来。工质为溴化锂溶液时,随着溶液浓度的增大,两级气泡泵泵起所需要的压差也是增大的。以水为工质时,气泡泵的启动时间随浸没高度的增大而减小。在以溴化锂溶液为工质时,启动时间在浓度为 45.5% − 54% 范围内时随着浓度的增大而增大。在浓度为 54% − 59.5% 时,随着浓度的增大而减小。在浓度为 54% 时气泡泵的启动时间达到最大值。

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(丛　敏　编辑)

平直斜翅管污垢特性研究 = Study of the Characteristics of Foul on Smooth and Straight Obliquely-finned Tubes［刊，汉］ **ZHOU Zhi-gang，YOU Xiao-kuan，ZHANG Hua（College of Energy Source and Power Engineering，**Shanghai University of Science and Technology，Shanghai，China，Post Code：200093），XU Hua（Equipment Repairing Factory，Jinan No. 4 Aviation Station，Air Forces of the People's Liberation Army of China，Jinan，China，Post Code：250022）//Journal of Engineering for Thermal Energy & Power. －2015，30（1）. －48－53

Through a dynamic fouling test of a smooth and straight obliquely-finned tube and bare tube at various calcium carbonate concentrations and flow speeds，obtained was the influence of the calcium carbonate concentration，fluid flow speed and tube type on the fouling process of calcium carbonate. The test results show that to increase the flow speed of the calcium carbonate solution will mainly result in an increase of the peeling-off force of the foul on the tube surface，thus decreasing the fouling speed and amount of foul produced，when the flow speed will reduces by a half，the thermal resistance value of the foul will increase by more than a fold. Relative to the calcium carbonate concentration of 0.5 mmol/L and 2.0 mmol/L，when such concentration is 1.0 mmol/L，the initial fouling speed and the amount of foul produced on the tube surface will be maximal and afterwards，because of the similar concentration in the solution，the thermal resistance value will gradually approach to each other. Albeit the smooth and straight obliquely-finned tube has a bigger heat exchange coefficient than the bare tube，yet，its foul-resistant performance is inferior to the latter，thus resulting to a higher fouling speed and more amount of foul and its progressive foul thermal resistance value is about 1.6 times higher than that of a bare tube. **Key Words：** pyrology，calcium carbonate，crystallization foul，obliquely-finned tube

两级气泡泵泵起现象的实验研究 = Experimental Study of the Pump Start-up Phenomenon of a Dual-stage Bubble Pump［刊，汉］ JU Xiao-qun（College of Shipbuilding and Oceanological Engineering，Harbin Institute of Technology（Weihai），Weihai，China，Post Code：264200）//Journal of Engineering for Thermal Energy & Power. －2015，30（1）. －54－57

Through the establishment of a test rig，with water and lithium bromide solution at various concentrations serving as the working medium，a great deal of experimental study and analysis were conducted of the pump start-up phenomenon of a dual-stage bubble pump. It has been found that to heat by using the lithium bromide steam constitutes a factor to start up the second stage bubble pump and another factor for the starting-up is attributed to the bubbles formed by the pressure reduction and flashing of the intermediate solution. The pump start-up of the dual-stage bubble pump is relevant to the pressure difference of the intermediate solution and the first-stage lithium bromide steam. When the working medium is water, in the case of the pressure difference of the first-stage lithium bromide steam and the intermediate solution is between 3.5 kPa and 3.8 kPa, the dual-stage solution pump can be put into operation and the start-up time duration will decrease with an increase of the submerging height. When the working medium is lithium bromide solution, with an increase of the solution concentration, the pressure difference required for starting up the dual-stage bubble pump will increase and be greater than that when the working medium is water. The start-up time duration will increase with an increase of the concentration when the lithium bromide solution concentration is in a range from 45.5% to 54% while it will decrease with an increase of the concentration when the lithium bromide concentration falls in a range from 54% to 59.5%. When the lithium bromide solution concentration is 54%, the start-up time duration arrives at its maximum value. **Key Words:** dual-stage bubble pump, pump start-up phenomenon, intermediate solution, absorption type refrigeration, pressure difference

1 000 MW **双切圆锅炉低氮同轴燃烧系统的模拟分析 = Simulation and Analysis of the Low Nitrogen Coaxial Combustion System of a** 1 000 **MW dual-tangentially-fired Boiler** [刊,汉] JIANG Xiao-feng (Shanghai Power Generation Complete Equipment Design Research Institute, Shanghai, China, Post Code: 200240) //Journal of Engineering for Thermal Energy & Power. -2015, 30(1). -58-65

With a 1 000 MW single furnace and dual-tangentially-fired boiler in a power plant serving as an example, a numerical simulation method was used to analyze the characteristics of the flow field in its low nitrogen coaxial combustion system in the furnace. In this process, the distribution of physical variables such as the temperature and speed etc. in the single furnace dual-tangentially-fired boiler was obtained with the influence of the horizontally offset overfire air and separated overfire air (SOFA) on the slagging, flue gas temperature deviation and NO emissions etc. being identified. It has been found that the deviation of the flue gas speed of the dual-tangentially-fired combustion mode is less than that of the single-tangentially-fired combustion mode. The corners of a furnace are divided into hot corners and cold ones. Influenced by the distribution of the cold corners, only a moderate air speed of the horizontally offset overfire air can lead to the "coal-surrounded-by-air" characteristics and prevent from slagging. The reverse tangential supply of the separated overfire air can force the thermal deviation of the heating surfaces to decrease, the center of the flame to move upwards and NO concentration to gradually increase. In such a case, the setting of the SOFA swaying angle should be taken into consideration in a comprehensive way depending on the safety of the heating surfaces, coal characteristics and NO emissions. **Key Words:** single furnace and dual-tangential, low nitrogen coaxial combustion system, horizontally offset overfire air, separated overfire air (SOFA), slagging, thermal deviation