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热泵辅助无规填料表面蒸发装置浓缩热敏料液性能研究

Study on the performance of heat pump assisted random filler surface evaporation device for concentrated thermosensitive feed liquid

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摘要:目的:设计一种低能耗、可在常压下低温浓缩热敏料液的表面蒸发浓缩装置。**方法:**建立装置的基本方程,分析体积蒸发通量和节能倍率随料液流量、料液温度、吹扫气流量、吹扫气温度的变化规律,制作试验台并通过试验得出一组最佳性能参数。**结果:**当料液流量为 0.02 kg/s 时,装置具有最高的节能倍率和较高的体积蒸发通量;当料液温度从 30 ℃增加到 50 ℃时,体积蒸发通量增加了 224.68%,但节能倍率降低了 12.42%;当吹扫气流量从 0.004 kg/s 增加到 0.006 kg/s 时,体积蒸发通量增加了 23.45%,但节能倍率降低了 7.74%;当吹扫气温度从 10 ℃增加到 30 ℃时,体积蒸发通量减少了22.92%,但节能倍率升高了 37.49%;以糖度为 15 °Brix 的橙汁进行测试,当料液温度为 38 ℃、吹扫气温度为26 ℃时,装置的体积蒸发通量可达 219 kg/(m^3·h),节能倍率可达 3.3。**结论:**热泵辅助无规填料表面蒸发装置浓缩热敏料液时具有常压下低温浓缩、能耗低等特点。

关键词:热敏料液;橙汁;浓缩;无规填料;表面蒸发;热泵

Abstract: Objective: A surface evaporation concentration device were designed to concentrate thermosensitive feed liquid at low temperature under normal pressure with low energy consumption. **Methods:** Based on an introduction to the working principle of the device, the basic equations of the device were given. The changes of volumetric evaporation flux and energy saving ratio with flow rate of the feed liquid, feed liquid temperature, sweeping gas flow rate, sweeping gas temperature were calculated and analyzed. Designed an experimental platform and obtained a set of optimal performance parameters through experiments. **Results:** The results showed that when the flow rate of the feed liquid was 0.02 kg/s, the device had the highest energy saving ratio and higher volumetric evaporation flux; When the temperature of the feed liquid increased from 30 ℃ to 50 ℃, the volumetric evaporation flux increased by 224.68%, but the energy saving ratio decreased by 12.42%; When the sweeping gas flow rate increased from 0.004 kg/s to 0.006 kg/s, the volumetric evaporation flux increased by 23.45%, but the energy saving ratio decreased by 7.74%; When the temperature of the sweeping gas increased from 10 ℃ to 30 ℃, the volumetric evaporation flux decreased by 22.92%, but the energy saving ratio increased by 37.49%; An experimental device was established to test orange juice with a sugar content of 15 °Brix, the results showed that when the feed liquid temperature was 38 ℃ and the sweeping gas temperature was 26 ℃, the volumetric evaporation flux of the device could reach 219 kg/(m^3·h), and the energy saving ratio could reach 3.3. **Conclusion:** The heat pump assisted random filler surface evaporation device has the characteristics of low temperature concentration under atmospheric pressure and low energy consumption when concentrating thermosensitive feed liquid.

Keywords: thermosensitive feed liquid; orange juice; concentration; random filler; surface evaporation; heat pump

食品、化工、制药等领域有多种料液属热敏料液,其浓缩需要在较低温度下进行[1],常用的低温浓缩方法有真空沸腾蒸发浓缩[2-4]、膜浓缩[5-7]、冷冻浓缩等[8]。真空沸腾蒸发浓缩需要配置真空设备[9],对装置的耐压和密封等要求均较高;膜浓缩由于膜污染或膜亲水化等原因,膜的使用寿命相对较短,制约了其广泛应用[10];冷冻浓缩所析出的冰中会夹带料液溶质,造成料液中有益成分的损失[11]。而无规填料表面蒸发可以避免上述蒸发方式的缺陷,原理是料液在填料表面形成液膜,当料液温度

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升高时,料液表面的水蒸气压力高于空气中的,水蒸气会由液膜表面向空气中扩散并被流过料液表面的吹扫气带走而实现料液浓缩,其特点是可在常压下实现低温浓缩,无规填料清洗方便,且使用寿命可达 10 年以上[12-13];热泵具有高效制热的特性[14],可为装置低能耗供热。因此,研究拟以常压、低温、低能耗的热敏料液蒸发浓缩装置为目标,对装置结构进行设计,计算与分析影响装置性能的因素,制作实验台并探究装置的浓缩性能,旨在为热敏料液蒸发浓缩的产业化应用提供依据。

1 装置工作原理

热泵辅助无规填料表面蒸发装置工作原理如图 1 所示。

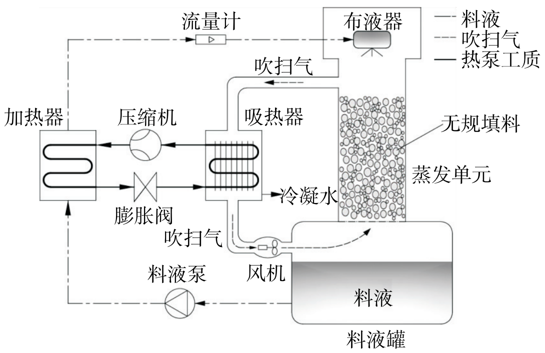

图 1 装置工作原理

Figure 1 Principle of the device

热泵辅助无规填料表面蒸发装置包括热泵单元、料液循环单元和吹扫气循环单元 3 个单元;其中热泵单元由压缩机、加热器、膨胀阀、吸热器构成,热泵工质在其中循环运行;料液循环单元由料液罐、料液泵、加热器、流量计、布液器、蒸发单元(蒸发单元内填充无规填料,无规填料上方设置布液器)构成,料液在其中循环运行;吹扫气循环单元由风机、蒸发单元、吸热器构成,吹扫气在其中循环运行(吹扫气通常为空气,当料液中含有易氧化成分时,吹扫气也可采用氮气、二氧化碳等[15])。

工作过程:热泵工质通过吸热器从富含水蒸气的吹扫气中吸热,经压缩机升压升温后进入加热器加热流过的料液;被加热到一定温度的料液经布液器分布到蒸发单元内的无规填料表面,在填料表面形成液膜;料液中的水分在液膜表面汽化为水蒸气,且液膜表面的水蒸气压力高于流过液膜表面的吹扫气中的,使液膜表面产生的水蒸气不断进入吹扫气中并被吹扫气带出蒸发单元;富含水蒸气的吹扫气流出蒸发单元进入吸热器后被热泵工质吸热降温,其中的水蒸气变为冷凝水排出,吹扫气再经风机返回蒸发单元继续循环;流出蒸发单元的料液中水分减小,变为浓度较高的浓缩液进入料液罐,被料液泵驱动进入加热器,经加热器升温后再返回蒸发单元继续循环浓缩,直到料液浓度达到规定值为止。

装置工作时,料液中水分的蒸发过程是依靠常压料液表面和常压吹扫气中的水蒸气压差实现的,因此在常压低温下对料液进行浓缩;料液中水分汽化所需的热能主要由热泵吸收吹扫气余热提供,压缩机、料液泵和风机只需要消耗少量电能来驱动各介质循环,因此可实现料液浓缩的低能耗;装置中除热泵外其他部件材料均可采用高分子材料(热泵加热器和热泵吸热器也可采用高分子材料换热器[16]),且使用寿命可在 10 年以上,因此装置的成本可较低。

2 装置性能模拟分析

2.1 装置基本方程

(1) 蒸发单元方程[17]:

$$m_{sv}=\frac{4M_wA_sh_m}{\pi RD^2L}\left(\frac{p_{sv}}{T_{fm}}-\frac{p_{av}}{T_a}\right), \tag{1}$$

$$A_s=\frac{m_sL}{u_sH\rho_s}, \tag{2}$$

$$h_m=\frac{h}{p_ac_p(Sc_a/Pr_a)^{0.67}}, \tag{3}$$

$$h=\frac{Nu\lambda_a}{d}, \tag{4}$$

$$Nu=2+(Re^{0.5}+0.06Re^{0.67})Pr_a^{0.4}, \tag{5}$$

$$Q_h=0.25\pi D^2Lm_{sv}h_{VL}+hA_s(T_{fm}-T_a), \tag{6}$$

式中:

m_{sv}——体积蒸发通量(单位时间内单位体积蒸发单元从料液中蒸发出的水分质量),kg/(m³·s);

M_w——水的摩尔质量,kg/mol;

A_s——料液在填料表面的液膜面积,m²;

h_m——液膜表面水蒸气向吹扫气中扩散的对流传质系数,m/s;

p_{sv}——料液表面的水蒸气压力,Pa;

p_{av}——吹扫气中的水蒸气压力,Pa;

R——气体常数,J/(mol·K);

D——蒸发单元内直径,m;

L——蒸发单元高度,m;

T_{fm}——液膜温度,K;

T_a——吹扫气温度,K;

m_s——料液流量,kg/s;

u_s——料液向下流动速度,m/s;

H——液膜厚度,m;

ρ_s——料液密度,kg/m³;

h——吹扫气与液膜的对流换热系数,W/(m²·℃);

p_a——吹扫气压力,Pa;

c_p——吹扫气定压比热容,J/(kg·K);

Sc_a——吹扫气的施密特数;

Pr_a——吹扫气的普朗特数;

Nu——对流换热努塞尔数;

λ_a——吹扫气导热系数,W/(m·℃);

d——液膜特征尺寸，m；

Re——吹扫气流动雷诺数；

Q_h——蒸发单元热负荷，W；

h_{VL}——料液中水分的汽化潜热，J/kg。

（2）热泵基本方程[14]：

$$COP=\frac{C_{hp}T_{rc}}{T_{rc}-T_{re}}, \quad (7)$$

$$P_c=\frac{Q_h}{COP}, \quad (8)$$

式中：

COP——热泵制热系数；

C_{hp}——热泵热力学完度系数；

T_{rc}——热泵工质冷凝温度，K；

T_{re}——热泵工质蒸发温度，K；

P_c——热泵压缩机功率，W。

（3）装置节能倍率：

$$ESR=\frac{0.25\pi D^2 Lm_{sv}h_{VL}}{P_c}, \quad (9)$$

式中：

ESR——装置节能倍率（相对于单效真空沸腾蒸发的节能倍数）。

2.2 装置性能分析

热泵辅助无规填料表面蒸发装置的主要性能指标为体积蒸发通量和节能倍率，基于式(1)～式(9)，装置性能随料液流量、料液温度（料液进蒸发单元温度）、空气流量、吹扫气温度（吹扫气进蒸发单元温度）的变化规律如图 2～图 5 所示（计算背景：无规填料为聚丙烯多面空心球，直径为 25 mm；蒸发单元内直径为 0.1 m，高度为 0.6 m；料液为橙汁，吹扫气为空气）。

图 2～图 5 中，料液流量过小时无法有效实现液膜铺展，流量过大时易形成沟流，当料液流量为 0.020 kg/s 时，装置具有最高的节能倍率和较高的体积蒸发通量；当料液温度由 30 ℃升高至 50 ℃时，液膜表面水蒸气压力增加，水蒸气由液膜向吹扫气扩散的传质压差增加，使体积蒸发通量升高了 224.68%，而料液温度升高导致热泵工质的冷凝温度升高，热泵制热系数降低，压缩机功率增加，使装置节能倍率降低了 12.42%；当吹扫气流量由 0.004 kg/s 增加至 0.006 kg/s 时，液膜表面水蒸气向吹扫气中扩散的传质系数增加，使体积蒸发通量升高了

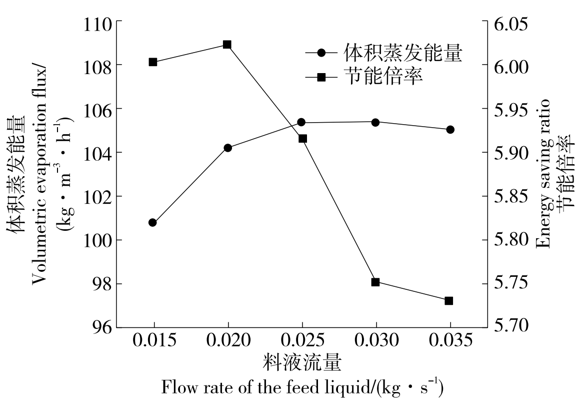

图 2　料液流量对装置性能的影响

Figure 2　Effects of flow rate of the feed liquid on device performance

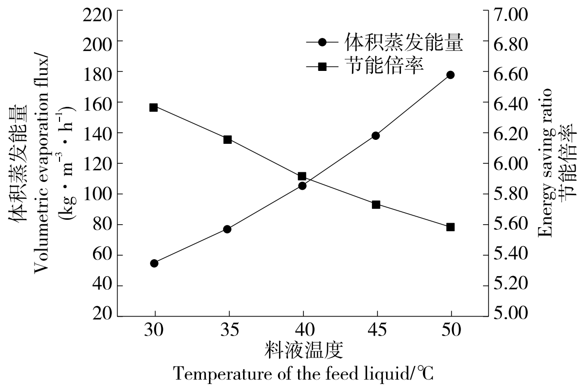

图 3　料液温度对装置性能的影响

Figure 3　Effects of feed liquid temperature on device performance

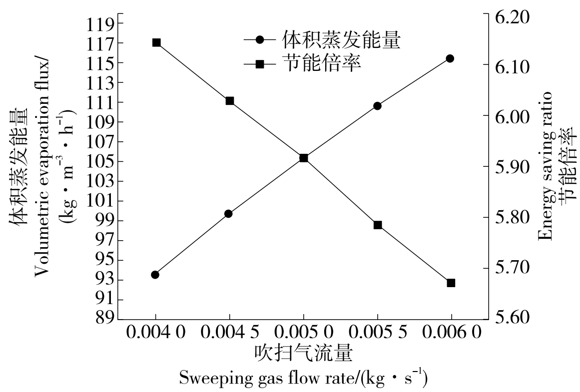

图 4　吹扫气流量对装置性能的影响

Figure 4　Effects of sweeping gas flow rate on device performance

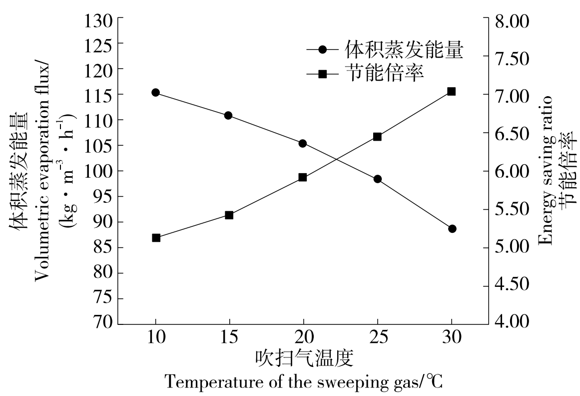

图 5　吹扫气温度对装置性能的影响

Figure 5　Effects of sweeping gas temperature on device performance

23.45%，但吹扫气流量增加使流出蒸发单元吹扫气的温度降低，导致热泵工质蒸发温度降低，热泵制热系数下降，压缩机功率增加，使装置节能倍率下降了7.74%；当吹扫气温度由10 ℃增加至30 ℃时，吹扫气中水蒸气压力也增加，使液膜表面水蒸气向吹扫气中扩散的传质压差减小，体积通量降低了22.92%，吹扫气温度升高使吸热器中热泵工质蒸发温度升高，热泵制热系数增加，压缩机功率减小，装置节能倍率增加了37.49%。

3 装置性能测试

以图1所示装置工作原理为参考，制作了热泵辅助无规填料表面蒸发试验装置。装置中热泵工质采用R134a，压缩机采用24 V直流变频转子式压缩机（高品ZH2024A），转速为1 800～6 000 r/min，吸气压力为0.2～0.5 MPa，排气压力不大于1.6 MPa；蒸发单元内直径为55 mm，高500 mm；无规填料采用聚丙烯多面空心球，直径为25 mm。

试验料液为15 °Brix的橙汁，吹扫气为空气；装置的运行性能见表1。

基于表1中运行参数，对装置性能进行模拟计算结果表明：装置体积蒸发通量计算值为159 kg/(m³·h)、装置节能倍率计算值为4.4；与表1进行对比，装置体积蒸发通量试验值高于计算值，这是由于料液在蒸发单元内的填料表面流动时，也会流动到蒸发单元壳体的内表面上，增加了料液的蒸发面积；装置节能倍率的试验值低于计算值，主要是由于试验装置规模较小，压缩机效率相对较低，同时装置的散热损失较大。

4 结论

研究设计了一种用于蒸发浓缩热敏料液的装置。结果表明，该装置具有可行性且浓缩热敏料液时具有常压下低温蒸发、能耗低等特点；体积蒸发通量随料液温度、吹扫气流量的增大而增大，随吹扫气温度的增大而减小；装置节能倍率随料液温度、吹扫气流量的增大而减小，随吹扫气温度的增大而增大；当试验料液为15 °Brix的橙汁、料液温度为38 ℃、吹扫气温度为26 ℃时，试验装置的体积蒸发通量可达219 kg/(m³·h)，节能倍率可达3.3，但该装置在实际应用中需要根据热敏料液的特性优选无规填料的最佳结构与材料。

表1 试验装置运行性能

Table 1 Performance of experimental device

项目	单位	数值
吹扫气流量	g/s	4.25
吹扫气进蒸发单元温度	℃	26.0
吹扫气进蒸发单元相对湿度	%	72.6
吹扫气出蒸发单元温度	℃	33.1
吹扫气出蒸发单元相对湿度	%	99.7
料液流量	g/s	7.58
料液进蒸发单元温度	℃	38.0
料液出蒸发单元温度	℃	30.7
体积蒸发通量	kg/(m³·h)	219
装置浓缩速率	kg/h	0.26
装置节能倍率		3.3
压缩机功率	W	57.0

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(上接第 103 页)

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