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基于CFD模拟的喷射泵操作参数对泵抽气性能的影响

韩 宇, 郭立新, 王晓冬, 张光利
(东北大学 机械工程与自动化学院, 辽宁 沈阳 110819)

摘 要: 通过CFD方法讨论了不同操作参数对喷射泵内部流体的流动特性及泵抽气性能的影响.随着工作蒸汽压力的增加,在壅塞位置处,被抽气体过流面积变化减小,马赫数、引射系数升高,喷射泵的抽气性能增强.当工作蒸汽压力过高时,由于膨胀核的增大,被抽气体的过流面积减小,引射系数显著下降.随着引射蒸汽压力的增加,壅塞和激波向下游移动,泵抽气性能增强.此外,引射系数随着背压的增加而减小,当背压过高时,返流现象明显,泵的抽气性能急剧下降直至失效.研究结果表明,操作参数的选择不仅能提高喷射泵的抽气效率和极限排气能力,也极大地提高了喷射制冷系统的制冷效率,降低了能源的消耗.

关 键 词: 喷射泵;壅塞;激波;引射系数;背压
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Influence of Operating Parameters on the Ejector Performance Based on CFD Simulation

HAN Yu, *GUO Li-xin*, *WANG Xiao-dong*, *ZHANG Guang-li*
(School of Mechanical Engineering & Automation, Northeastern University, Shenyang 110819, China. Corresponding author: WANG Xiao-dong, E-mail: xdwang@mail.neu.edu.cn)

Abstract: The influences of the different operating parameters on flow characteristic of internal flow field and the ejector performance are discussed by CFD method. With the increase of the primary fluid pressure, the flow area of the secondary fluid pressure decreases at the choking position, however, the Mach number and the entrainment ratio both gradually increased, and the pumping performance is enhanced. When the pressure is too high, the flow region of the secondary fluid is compressed due to the increase of the expansion core and the entrainment ratio decreases obviously. With the increasing of the primary fluid pressure, the choking position and the shock wave moves downstream. The pumping performance of the ejector is strengthened. The entrainment ratio decreases with the increase of the back pressure. When the back pressure is too high, the reflux phenomenon is obvious and the pumping performance decreases sharply until it loses efficiency. The results indicated that the reasonable selection of the operating parameters can not only improve the pumping efficiency and exhaust capacity of the ejector, but also greatly improve the refrigeration efficiency of jet refrigeration system and reduce the energy consumption.

Key words: ejector; choke; shock wave; entrainment ratio; back pressure

随着全球能源问题的日益突出,人们对于环境保护的意识不断提升,国际上针对节约和循环再利用能源的措施也不断地被提出[1].开发利用工业余热和太阳能等可循环热源和清洁能源驱动的设备和装置成为现阶段研究的重点[2-3].水蒸气喷射制冷系统因其结构简单、工作介质环保和经济好等优点而受到了广泛的关注[4].系统主要由发生器、喷射泵、冷凝器和蒸发器等主要元件组

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作者简介: 韩 宇(1985-),女,辽宁抚顺人,东北大学博士研究生;郭立新(1968-),男,辽宁沈阳人,东北大学教授,博士生导师;王晓冬(1963-),男,辽宁沈阳人,东北大学教授.

成.其工作过程为水经过发生器加热后汽化成水蒸气并以高速度进入到喷射泵,并在喷射泵入口处产生较低的压力使蒸发器内的水蒸气通过压差进入到喷射泵并带走相应的热量从而达到制冷效果.而混合后的水蒸气经喷射泵排出后进入到冷凝器继续制冷循环[5].喷射泵是影响整个制冷系统效率的关键元件[6-8].喷射泵的作用是工作介质在经过喷嘴加速后达到超音速状态并携带引射蒸汽进入到混合室,在混合室内两种工作蒸汽进行了剧烈的能量和动量交换后经扩压器减速增压后排出.喷射泵内的流体流动是一种跨音速的复杂流动行为,流体的流动状态直接影响到喷射泵的抽气性能[9-11].

近年来,关于喷射泵中流体流动与传热的数值模拟分析引起了广大研究者的关注[12],主要研究集中在喷射泵的结构改进与性能优化方面.但对于喷射泵内部流体流动特性的研究仍处于空白阶段.由于喷射泵内部流体流动速度过快,尽管有PIV测试等高新技术的出现[13],然而高昂的价格仍是限制其应用和推广的原因所在.经济性好并能满足实验要求的方法尚未出现.由此带来的喷射泵理论模型的适用性和数值方法的正确性缺乏实验数据支持等问题,在一定程度上限制了数值模拟方法的推广及应用.

现阶段的研究表明喷射泵抽气性能主要受工作蒸汽参数、被抽气体参数以及喷射泵几何参数等因素影响.在壅塞条件下,被抽气体的过流面积和速度是影响喷射泵抽气性能的决定性因素[14-15].本文通过CFD模拟分析,得到了不同操作参数条件下对喷射泵引射系数的影响以及对泵抽气性能的影响,为提高喷射泵的效率、优化和改进喷射泵的结构提供了全面的理论分析.

1 CFD方法

1.1 控制方程

水蒸气喷射泵的内部流体的流动通常是不可压缩的、稳定的和轴对称的.考虑流体黏性耗散和温度的影响,控制方程[16]为

质量方程:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0; \tag{1}$$

动量方程:

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial P}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}; \tag{2}$$

能量方程:

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_i}(u_i(\rho E+p))=\vec{\nabla}\left(\alpha_{\mathrm{eff}}\frac{\partial T}{\partial x_i}\right)+\vec{\nabla}(u_j(\tau_{ij})). \tag{3}$$

1.2 几何结构和网格划分

采用文献[17]实验系统中的喷射泵为计算几何模型,根据Pianthong和Seehanam[18]的结论,3D模型和2D模型进行计算时其模拟结果非常接近,为了节省计算时间和降低计算成本,本文采用二维轴对称模型.

对喷射泵的内部流场进行结构化网格划分并在局部速度较大的区域进行加密,如图1所示.网格质量为0.9以上,最大纵横比为5:1,网格质量较高.通过比较图2中不同网格密度下中心线马赫数分布曲线可知,中等网格和细网格的变化趋势几乎相同,为了提高计算效率,在后续的模拟过程中均采用中等网格,网格数为46 352,同时网格的独立性得到验证.

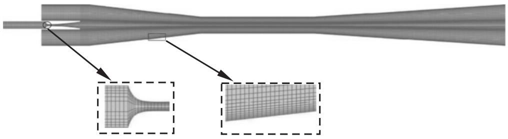

图1 喷射泵的结构化网格

Fig. 1 Structured grid of steam ejector

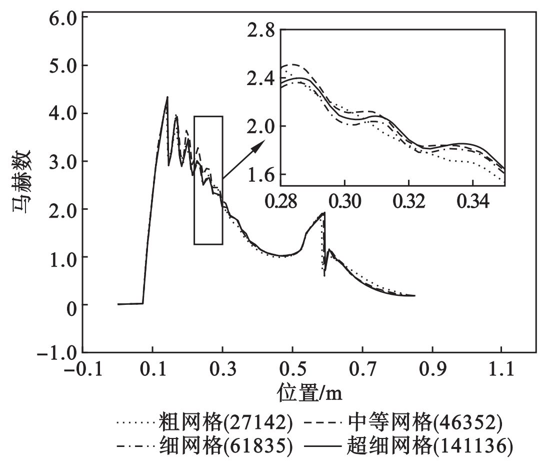

图2 网格独立性验证

Fig. 2 Grid independence verification

1.3 数值模拟设置

采用基于ANSYS的计算流体力学软件FLUENT18.0进行模拟分析.采用耦合隐式求解器,扩散项采用中心差分格式进行离散,离散系统通过高斯-塞德尔迭代法计算,时间离散迭代方法选用多重Runge-Kutta显式格式迭代,所有的对流项采用二阶迎风格式离散求解.选择能预测喷射泵内复杂流动的realizable $k-e$ 为湍流模型,入口处的湍流强度为5%.壁面采用无滑移条件,且视为绝热等熵流动,近壁面处理方法采用加强

壁面函数且 $y+\approx 0.86<1$. 进出口分别设置为压力入口和压力出口. Besagni 等[19-20]已经证实了蒸汽的密度与理想气体模型中真实气体所获得的密度没有太大差别. 因此本文工作流体采用理想气体模型,其具体参数如表 1 所示.

表 1　工作流体的物理属性
Table 1　Properties of the working fluid

属性	数值
密度	理想气体
动力黏度/($kg\cdot m^{-1}\cdot s^{-1}$)	1.34×10^{-5}
热导率/($W\cdot m^{-1}\cdot K^{-1}$)	0.026 1
比热容/($J\cdot kg^{-1}\cdot K^{-1}$)	2 014

2　结果和讨论

喷射泵流体除存在跨音速流动外还存在激波、壅塞和混合等复杂的流动现象. 为了提高喷射泵的效率模拟了不同操作参数下喷射泵性能变化的情况.

2.1　工作蒸汽压力的影响

采用已被验证的 CFD 模型[21]和本组实验设备[6]进行数据测量,得到在蒸发温度为 25 ℃,被抽气体压力为 3 170 Pa,背压为 4 000 Pa 的条件下,不同工作蒸汽压力与引射系数的关系如图 3 所示. 随着工作蒸汽压力的升高,引射系数呈现先增大后减小的趋势,当蒸汽压力达到0.36 MPa时引射系数最大,此时喷射泵的抽气性能最好、抽气效率最高.

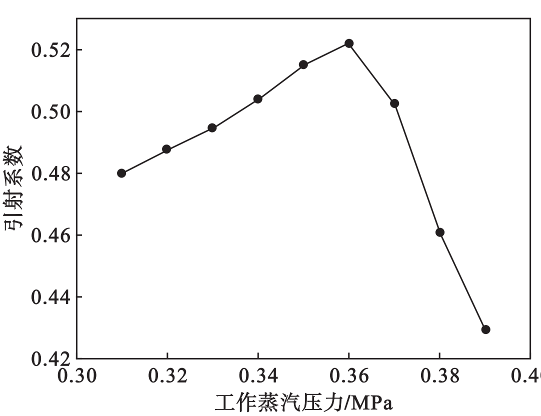

图 3　引射系数与工作蒸汽压力的关系
Fig. 3　Relationship between the entrainment ratio and the primary fluid pressure

图 4 为喷射泵 1 马赫数以上的速度云图,引射气体在距壁面 1 mm 处的马赫数曲线如图 5 所示. 综合两图可知,当工作蒸汽压力低于0.36 MPa时,在壅塞位置处,被抽气体的过流面积基本相同,喉部出口处的正激波位置没有变化,混合流体的速度逐渐增大,引射系数增加,喷射泵效率提高;当工作蒸汽压力高于 0.36 MPa 时,在壅塞位置处工作蒸汽的膨胀核增大,压缩了被抽气体的流动通道,使被抽气体的过流面积急剧减小导致被抽气体的质量流量减小. 随着工作蒸汽压力的增加,壅塞位置处的速度逐渐增大但引射蒸汽的质量流量却随工作蒸汽压力的提高而减小,导致引射系数减小,喷射泵效率降低.

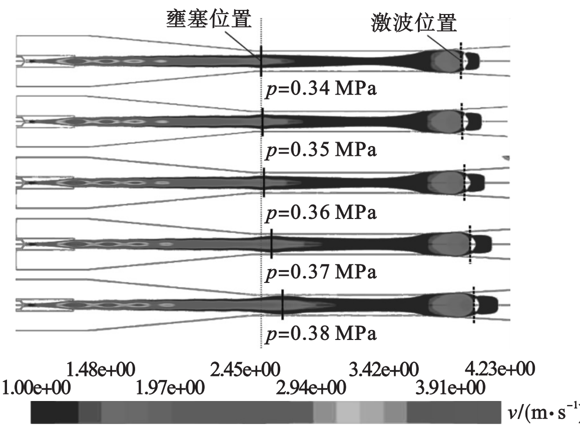

图 4　不同工作蒸汽压力下工作蒸汽的马赫数云图
Fig. 4　Contours of Mach number of working steam under different working steam pressure

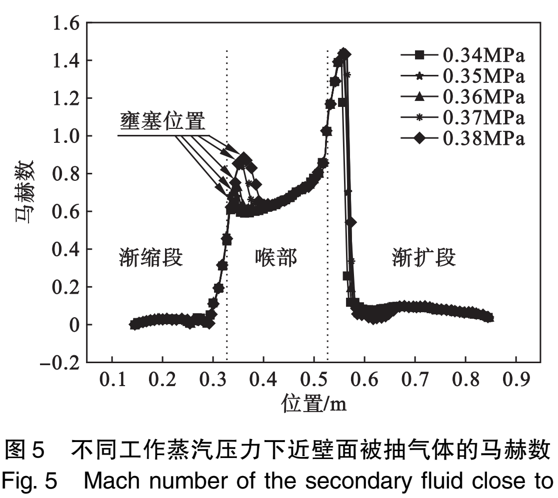

图 5　不同工作蒸汽压力下近壁面被抽气体的马赫数
Fig. 5　Mach number of the secondary fluid close to the wall under different primary fluid pressure

2.2　引射蒸汽压力的影响

引射蒸汽压力与引射系数的关系如图 6 所示. 随着引射蒸汽压力的升高,引射系数增大,喷射泵的效率升高. 其原因是引射蒸汽压力越高,工作蒸汽通过拉瓦尔喷嘴之后膨胀的扩散角度就越小,引射蒸汽的过流面积变大,引射蒸汽处于壅塞状态时通过的质量流量增加而通过拉瓦尔喷嘴的工作蒸汽没有变化,故引射系数增大. 同时正激波位置向下游移动(图 7)更加有效地降低了背压对流动的影响,有利于提高泵的抗背压能力,喷射泵

运行更加平稳.

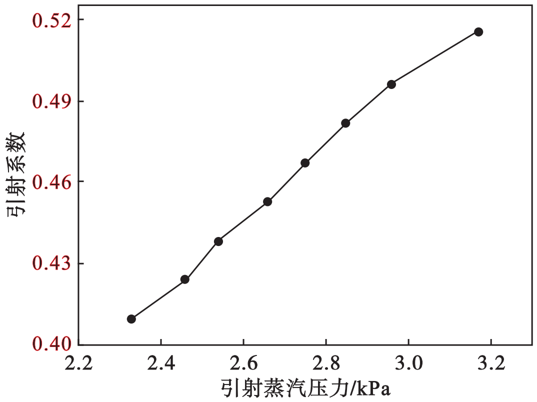

图 6 引射系数与引射蒸汽压力的关系
Fig. 6 Relationship between the entrainment ratio and the secondary fluid pressure

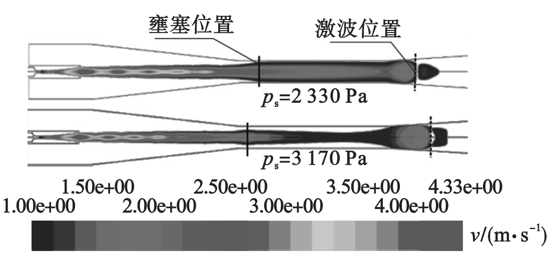

图 7 不同引射蒸汽压力下的马赫数云图
Fig. 7 Contours of Mach number under different secondary fluid working pressure

2.3 背压的影响

当工作蒸汽压力为 0.36 MPa,被抽气体压力为 3 170 Pa 时,不同背压下 1 马赫数以上的速度云图如图 8 所示. 在背压小于 4 500 Pa 时,由于激波的产生,超声速的无黏主流体阻止了由于背压变化引起的扰动向上游的传播,使喉部内发生壅塞的位置和过流面积均相同. 随着喉部出口处的正激波位置向上游移动,被抽气体距壁面 1 mm 处的马赫数未发生变化,如图 9 所示,因此引射系数不变. 当背压超过 4 500 Pa 时,在喉部近出口位置处未产生正激波,下游背压引起的扰动向上游扩散从而导致引射气体不能发生壅塞,造成引射气体的马赫数显著下降,发生返流现象. 引射系数急剧下降直至为零,此时喷射泵失效再无抽气能力.

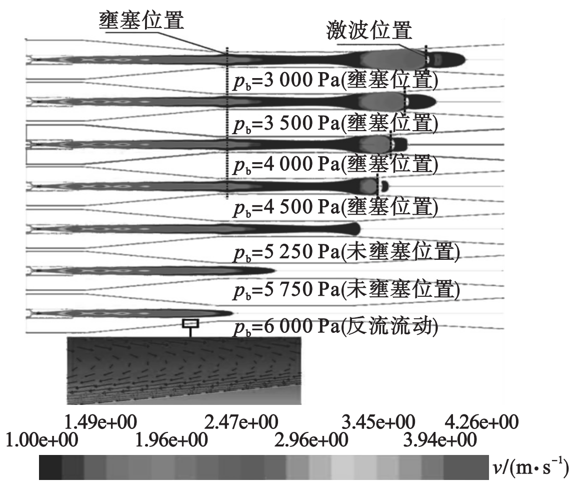

图 8 不同背压下的马赫数云图
Fig. 8 Filled contours of Mach number of back pressure

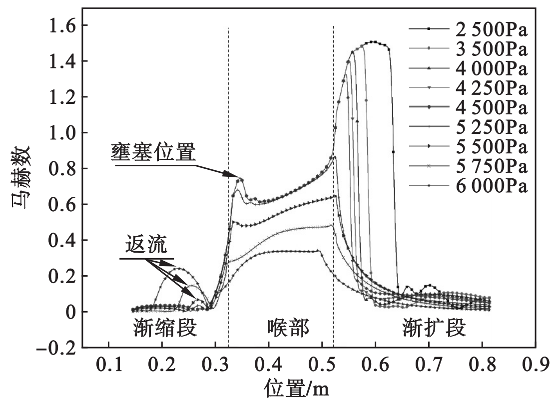

图 9 不同背压下近壁面被抽气体的马赫数
Fig. 9 Mach number of pumped gas close to the wall at different back pressure

3 结 论

1) 喷射泵过高的工作蒸汽压力使射流膨胀核变大,减少了被抽气体的过流面积,导致引射系数随之下降,喷射泵效率降低.

2) 当工作蒸汽压力为 0.36 MPa,被抽气体压力为 3 170 Pa 时,喷射泵的临界背压为 4 500 Pa 左右;当背压低于临界背压时,引射系数不变;当背压高于临界背压时,引射系数明显减少;背压过高时,引射系数接近于零,喷射泵失效.

3) 对于特定喷射制冷系统除兼顾抽气效率和极限排气能力外,在前级泵能够提供的压力范围内极大地提高了喷射系统的抽气效率.

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