# 管内单相流强迫对流湍流传热关联 式研究



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摘 要:管内单相流强迫对流湍流传热广泛应用于各个工业领域。目前有很多管内单相流强迫对流湍流传热关联式,需要 对其计算精度进行评价分析,便于选用。本文通过试验,获得了46组R134a在水平圆铜管内的单相流强迫对流湍流传热数 据,从23篇文献中收集了1220组试验数据,建立了一个含有1266组数据的管内单相流强迫对流湍流传热试验数据库。用 这个数据库对14个现有管内单相流强迫对流湍流传热关联式进行了评价分析,鉴别出了预测精度高的关联式,为管内单相 流强迫对流湍流传热关联式的选用提供了依据。

关键词:强迫对流,管内,传热,关联式,湍流,单相流

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管内单相流强迫对流(简称管内强迫对流)湍流传热广 泛应用于航空航天、能源建筑、石油化工等各个工业领域, 如航空领域的飞机环境控制系统、动力系统、燃油系统等。 相关设备和系统的研发设计离不开管内强迫对流湍流传热 的计算,因此许多研究者提出了管内强迫对流湍流传热关 联式。

随着航空航天技术和微电子技术的发展,大功率高密度 电子设备的冷却提出了两相流传热技术的需求。研究发现, 大多数两相流传热模型是在单相流传热模型的基础上发展 而来的,最常见的是基于Dittus-Boelter<sup>[1]</sup>公式的传热模型, 其次是基于Gnielinski<sup>[2]</sup>公式的传热模型。因此,单相流传热 关联式的准确性也直接影响两相流传热计算的准确度。

目前公开报道的管内强迫对流湍流传热关联式很多, 这一方面给工程应用带来了方便,另一方面也给关联式的 选用带来了困惑。使用者往往不知道该选用哪个关联式。 为此,本文一方面广泛收集整理管内强迫对流湍流试验数 据,并通过试验获得部分数据,建立试验数据库;另一方面 收集现有传热关联式。在此基础上,利用试验数据对关联

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式进行评价分析,获得各关联式对数据库的预测精度,为管 内强迫对流湍流传热关联式的选用提供依据。

# 1 管内强迫对流湍流传热的试验研究

## 1.1 试验装置

试验装置如图1所示,主要由试验段、冷凝器、储液罐、过 冷器、齿轮泵、流量计以及预热段组成。试验段为光滑圆铜 管,内径分别为1.002mm和2.168mm,长200mm,水平放置。





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#### 1.2 试验结果和不确定度分析

本试验共获得46组R134a在水平圆管中的强迫对流湍流传热试验数据。限于篇幅,数据整理过程不予详述。试验参数范围见表1。试验的不确定度根据Kline和 McClintock<sup>[3]</sup>提出的方法确定,见表2。

表1 参数试验范围 Table 1 Experimental range of parameters

内径/mm	质量流速/	热量密度/	泪座/℃	压力/MPa	
	$(kg/m^2 \cdot s)$	$(kW/m^2)$	(Ⅲ)支/ C		
1.002	608~1545	4.6~31.1	16.1~30.0	0.586~0.820	
2.168	1154~3020	14.0~36.7	16.0~21.0	0.788~0.799	

表2 不确定度 Table 2 Experimental uncertainty

参数	不确定度
内径	$\pm 1 \mu m$
长度	±1mm
温度	±0.1°C
质量流量	±1.0%
相对压力	±0.5%FS
大气压力	±100Pa
压差	±0.075%FS
热流密度	±1.79%
传热系数	±8.95%

# 2 从现有文献中获得的管内强迫对流湍流传 热试验数据

除了通过试验获得的46组R134a管内强迫对流湍流传 热试验数据外,从23 篇已经发表的文献中收集了1220组试 验数据,见表3。表中的试验数据参数范围为:雷诺数Re =3040~651357,普朗特数Pr = 0.9~7.3,热流密度q = 2~34468kW/m<sup>2</sup>,质量流速G = 139~39832kg/(m<sup>2</sup>·s),水力直径 D = 0.25~17.68mm,包含了水、氮、二氧化碳、氩、R134a、 RC318和R113等7种工质。

# 3 管内强迫对流湍流传热关联式

研究者提出了很多管内强迫对流湍流传热关联式,本 文收集整理了14个,分别是Dittus-Boelter<sup>[1]</sup>,Gnielinski<sup>[2]</sup>, Sieder - Tate<sup>[27]</sup>,Petukhov - Kirillov<sup>[28]</sup>,Adams<sup>[29]</sup>,Heta<sup>[30]</sup>, Kakac<sup>[31]</sup>,Ghajar-Tam<sup>[32]</sup>,Hausen<sup>[33]</sup>,Choi<sup>[34]</sup>,Yu<sup>[35]</sup>,Wang-Peng<sup>[36]</sup>,Debray<sup>[37]</sup>和Wu-Little<sup>[38]</sup>等。由于篇幅限制,这里 只列出对于本文数据库预测精度较高的前5个关系式,见 表4。表中,f为Moody摩擦因数;D为管内径或水力直径, 单位为m,L为换热有效长度与热入口段长度的和,单位为 m; $\mu$ 为[动力]黏度,单位为Pa·s;下标w表示定性温度为壁 面温度,其他参数的定性温度为流体平均温度。

# 4 管内强迫对流湍流传热关联式的评价

本文采用平均绝对误差(MAD)作为评价管内强迫对 流湍流传热关联式预测精度的标准。MAD越小,预测精度 越高。

$$MAD = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{y(i)_{\text{pred}} - y(i)_{\text{exp}}}{y(i)_{\text{exp}}} \right|$$

此外,采用平均相对误差反映关联式在总体上是高估 (MRD > 0%)还是低估(MRD < 0%)了数据库。

$$MRD = \frac{1}{N} \sum_{i=1}^{N} \frac{y(i)_{pred} - y(i)_{exp}}{y(i)_{exp}}$$

利用上述试验获得的46组和从文献中收集到的1220 组管内强迫对流湍流试验数据组成的数据库,对14个管内 强迫对流湍流传热关联式进行评价分析。表5中列出了预 测精度最高的前5个关联式的评价结果。从表中可以看 出,预测精度最高的是 Gnielinski<sup>[2]</sup>关联式,MAD=19.5%。 Gnielinski<sup>[2]</sup>、Sieder-Tate<sup>[27]</sup>和 Ghajar-Tam<sup>[32]</sup>关联式对壁温 的影响进行了修正。这种修正有助于提高公式的预测精 度,但同时也增加了公式使用的困难。另外,在实际应用 中,由于壁温一般是未知条件,含有与壁温有关的参数会增 加公式预测的不确定性。综合分析可知,管内强迫对流湍 流传热关联式还需进一步深入研究。

图 2 和图 3 分别是 Gnielinski<sup>[2]</sup>公式和 Dittus-Boelter<sup>[1]</sup> 公式传热系数计算值与试验值的比较。可以看出,在传热 系数大于 60kW/(m<sup>2</sup>·K)时,Gnielinski<sup>[2]</sup>公式的计算精度显著 高于 Dittus-Boelter<sup>[1]</sup>公式的计算精度。

图 4 和图 5 分别是 Gnielinski<sup>[2]</sup>公式和 Dittus-Boelter<sup>[1]</sup> 公式努塞尔数计算值与试验值的比较。可以看出,当努塞 尔数 $Nu = 150 \sim 250$ 时,Dittus-Boelter<sup>[1]</sup>公式预测精度较高, 其他情况下,Gnielinski<sup>[2]</sup>公式预测精度较高。

法关于教	会粒范围. $T(^{\circ}C)/n(har)/G(kg/m^2 \cdot s)/a(kW/m^2)/工质$	几何参数:D(mm)/L(mm)/	粉据占粉
参与文献	South of the state	W(mm)/H(mm)/流向和管型	XX.1/11/1/XX
Liang <sup>[4]</sup>	108,103,108.5,109/12,11.4,11,10/241~374/16.8~44.1/7k	3.48/800/50/1.8/竖直矩形不锈钢管	30
Wang <sup>[5]</sup>	18.5/1/714~4491/44.4~279.1/7k	7.9/1200/NA/NA/水平圆管	42
Liu Li <sup>[6]</sup>	30/60/439~1679/4.8~18.4/ R152a	1.15/278/NA/NA/水平不锈钢圆管	15
Qi <sup>[7]</sup>	-188/4.3/859~9524/34.6~165.8/液氮	0.83/250/NA/NA/;0.531/250/NA/NA/;竖直不锈钢圆管	54
Ma <sup>[8]</sup>	36/1/719~2567/47.5~169.5/7k	3.64/1037/40/2/水平矩形不锈钢管	9
Adams <sup>[9]</sup>	62/10.3/1543~8600/500, 1000, 1500, 2000/7k	1.13/160/NA/NA/水平非圆形铜管	99
Tian <sup>[10]</sup>	63.1~93.4/1.8~3/288~480/6.6~44.5/7	3.81/550/40/2/竖直矩形不锈钢管	42
Wang <sup>[11]</sup>	51.5~80.5/8.5, 7.6, 8/410~1298/27.8~172.9/7k	3.81/1500/40/2/竖直矩形不锈钢管	82
Ducoulombier <sup>[12]</sup>	-12/26.5/851~1675/ 2.5~15/CO <sub>2</sub>	0.53/159.3/NA/NA/水平不锈钢圆管	48
Grohmann <sup>[13]</sup>	-171,-134/15/285~7306/8.7~263.4/氯	0.25/30/NA/NA/;0.5/30/ NA/NA/;水平铜圆管	43
Meyer <sup>[14]</sup>	20/1/740~1562/13/7k	5.16/1000/NA/NA/水平铜圆管	22
Aroonrat <sup>[15]</sup>	25/1/505~1242/3.5/7K	7.1/2000/NA/NA/水平不锈钢圆管	17
Fernando <sup>[16]</sup>	31.5/1/1679~3196/15.3~29.1/7k	1.42/651/2.65/1/竖直矩形铝管	29
Man <sup>[17]</sup>	45/1/139.3~331.7/12.7~18.7/7k	16/2400/NA/NA/水平不锈钢圆管	8
Bang <sup>[18]</sup>	14,25/7,14.5/2000,1000/5.3~138.5/ R134a	6.15/100/8/5/竖直矩形镍合金管	30
Sarwar <sup>[19]</sup>	25,50/1/300,200/25~131.7/7k	10.92/230/NA/NA/竖直不锈钢圆管	11
Hua <sup>[20]</sup>	40,50,60,70/1/192.4~1949.7/86.9~729.4/7k	17.68/90/24/14/水平矩形不锈钢管	270
Vlachou <sup>[21]</sup>	30/1/330~830/248.9~506.7/7k	16/120/40/10/; 5.58/120/40/3/;水平矩形铜管	49
Yan <sup>[22]</sup>	90/40/3804~14299.5/5000/7次	9/400/NA/NA/竖直镍合金圆管	58
Belyaev <sup>[23]</sup>	31~180/14.353~22.973/850~3600/12.5~276/RC318, R113	0.95/100/NA/NA/;1.36/200/NA/NA/;竖直不锈钢圆管	86
Hata和Masuzaki <sup>[24]</sup>	39.6/8/3970.7~13202.6/4140~12600/7jk	3/66.5/NA/NA/竖直铂圆管	38
Hata和Masuzaki <sup>[25]</sup>	30.6/8/3983.2~39831.6/3850~34467.9/7	6/49.1/竖直不锈钢圆管	52
Papell <sup>[26]</sup>	22.22~45.56/2.81~12.2/178.6~3778/606.7~2587/7]	7.9/165/NA/NA/水平不锈钢圆管	86
总计			1220

## 表3 管内强迫对流湍流传热试验数据统计表

Table 3 Surveyed experimental data of forced convection heat transfer of turbulent pipe flow

# 表4 预测精度最高的5个管内强迫对流湍流传热关系式

Table 4 Top five correlations of forced convection heat transfer of turbulent pipe flow

名称	形式
Gnielinski <sup>[2]</sup>	$\begin{split} Nu &= \frac{(f^{78})(Re - 1000) Pr}{1 + 12.7(f^{78})^{1/2}(Pr^{2/3} - 1)} \bigg[ 1 + \bigg( \frac{D}{L} \bigg)^{2/3} \bigg] \bigg( \frac{Pr}{Pr_w} \bigg)^{0.11} \\ f &= (0.79 \ln Re - 1.64)^{-2} \\ \vec{x} \oplus : \vec{q} ] \lambda [1 + (D/L)^{2/3}] \vec{z} \vec{e} . \vec{k} \lambda \Box \vec{Q} \vec{S} \vec{m}, \vec{q} ] \lambda (Pr/Pr_w)^{0.11} \vec{z} \vec{e} . \vec{k} \vec{k} a \vec{k} \vec{k} = \vec{p} \vec{k} \vec{k} \vec{k} \vec{k} \vec{k} \vec{k} \vec{k} k$
Dittus-Boelter <sup>[1]</sup>	$Nu = 0.023 Re^{0.8} Pr^n$ 其中:管内流体被加热时 $n=0.4$ ,被冷却时 $n=0.3$ 。
Sieder-Tate <sup>[27]</sup>	$Nu = 0.023 Re^{0.8} Pr^{\frac{1}{3}} \left(\frac{\mu_{\rm f}}{\mu_{\rm w}}\right)^{0.14}$
Petukhov-Kirillov <sup>[28]</sup>	$Nu = \frac{(f/8) RePr}{1.07 + 12.7 (f/8)^{1/2} (Pr^{2/3} - 1)}$ 其中:f由式(2)求得。
Ghajar–Tam <sup>[32]</sup>	$Nu = 0.023 Re^{0.8} Pr^{0.385} \left(\frac{L}{D}\right)^{-0.0054} \left(\frac{\mu}{\mu_{\rm w}}\right)^{0.14}$

Table 5 Evaluation results of top five correlations						
误差	Gnielinski <sup>[2]</sup>	Dittus- Boelter <sup>[1]</sup>	Sieder- Tate <sup>[27]</sup>	Petukhov– Kirillov <sup>[28]</sup>	Ghajar <del>–</del> Tam <sup>[32]</sup>	
MAD/%	19.5	21.4	23.3	23.4	24.2	
MRD/%	6.7	-6.8	3.2	1.0	6.6	

预测精度最高的5个关联式的评价结果



图 2 传热系数:Gnielinski<sup>[2]</sup>公式计算值与试验值的比较 Fig. 2 Heat transfer coefficients: predicted by Gnielinski<sup>[2]</sup> equation vs measured









Fig. 4 Error distribution of *Nu* number prediction of the Gnielinski<sup>[2]</sup> equation





# 5 结论

本文建立了一个由1266组试验数据组成的管内强迫 对流湍流传热试验数据库,包括作者试验获得的46组和从 现有文献中获取的1220组。用该数据库对14个管内强迫 对流湍流传热关联式进行了评价分析,可以得出以下结论:

(1)基于本文数据库,预测准确度最好的前5个关联式
 依次为 Gnielinski<sup>[2]</sup>, Dittus - Boelter<sup>[1]</sup>, Sieder - Tate<sup>[27]</sup>、
 Petukhov-Kirillov<sup>[28]</sup>和Ghajar-Tam<sup>[32]</sup>关联式,其MAD分别为19.5%、21.4%、23.3%、23.4%和24.2%。

表5

(2)在本文数据范围内,在传热系数大于60 kW/(m<sup>2</sup>·K) 时,Gnielinski<sup>[2]</sup>公式的计算精度显著高于Dittus-Boelter<sup>[1]</sup> 公式的计算精度;当 $Nu = 150 \sim 250$ 时,Dittus-Boelter<sup>[1]</sup>公式 预测精度较高,其他情况下,Gnielinski<sup>[2]</sup>公式预测精度 较高。

(3)Gnielinski<sup>[2]</sup>、Sieder-Tate<sup>[27]</sup>和Ghajar-Tam<sup>[32]</sup>关联式 引入了壁温影响的修正,实际应用中含有与壁温有关的参 数会增加公式预测的不确定性,当壁温和流体温度相差不 是很大时,可舍去壁温修正项。

(4)管内强迫对流湍流传热关联式的预测精度仍有待提高。 (A)

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# Study of Correlations of Forced Convection Heat Transfer of Single-phase Turbulent Pipe Flow

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**Abstract:** The forced convection heat transfer of single-phase turbulent pipe flow has been widely used in many industrial sectors. There are many correlations for the forced convection heat transfer of single-phase turbulent pipe flow, and the needs exist to evaluate their prediction accuracy to provide a guide for the users. The experiment investigation of the single-phase R134a flowing in horizontal copper circular tubes was conducted, yielding 46 turbulent forced convection heat transfer data, and another 1220 experimental data were compiled from 23 published articles, forming a database containing 1266 data. Based on the database, 14 correlations of the forced convection heat transfer of single-phase turbulent pipe flow were evaluated, and the correlations with higher prediction accuracy were identified, which provided a guide to the selection of such correlations.

Key Words: forced convection; pipe flow; heat transfer; correlation; turbulent; single-phase

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