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一维管道汽液两相流动的小波数值瞬态计算

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摘 要:小波分析是一种新兴的数学分析工具,运用此数值计算的方法对汽液两相流动的瞬态热工计算分析,这将是非常具有实际意义的。通过对汽液两相流动的小波数值瞬态计算结果与 Mini-TRAC 计算结果的比较,证明了这种数值方法完全可以用于对汽液两相流动的耦合微分方程组的瞬态计算。

关 键 词:小波分析;数值计算;汽液两相流

中图分类号:O359 文献标识码:A

符号说明

A—管道横截面积/m^2

D_e—管道当量直径/m

f—流体的摩擦阻力系数

g—重力加速度/m·s^{-2}

h—焓/kJ·kg^{-1}

p—压力/MPa

q_1—线加热热流密度/kW·m^{-1}

U_g—加热周长/m

W—质量流速/kg·s^{-1}

x—干度

α—空泡份额

ρ—汽液两相混合物密度/kg·m^{-3}

ρ_f—液相的密度/kg·m^{-3}

ρ_g—汽相的密度/kg·m^{-3}

Φ_{tp}^2—两相摩擦压降倍增因子

1 引 言

汽液两相流动与传热问题是一古老的问题,至少可以追溯到 18 世纪瓦特发明蒸汽机的时代[1]。尽管如此,近年来人们对两相流动与传热问题的研究仍热情不减[2~4],而且如何将近代其它学科领域的新思想、新观点和新方法应用于两相流动与传热分析中,更是现代对两相流研究的热点[2~4]。小波分析是近年来最具有活力和应用前景的数学工具和方法,目前它已在许多科学领域得到应用,并取得了巨大的成功和促进了这些科学领域的更进一步发展。但目前这一有力的工具,在对汽液两相流动与传热问题的研究中,还只是限于探索和辅助阶段[2~4]。其原因是由于汽液两相流动与传热这样的流体力学问题,其流动规律是受流体力学的基本方程控制的,即满足一定的流动规律,而要想知道两相流动的运动规律除了实验研究的手段外,就必须用数学方法去求解与两相流动有关的流体力学基本控制方程组。

近年来,小波分析已在很多领域得到应用,如信息图像处理、非线性科学及微分方程数值求解等方面,可以说是在工具和方法上的重大突破,但目前用小波分析作为数值计算的工具还只停留在理论研究上[5]。本文将利用小波分析方法作为对汽液两相流动热工分析的数值计算工具,将解决用小波分析数值计算方法求解复杂的耦合汽液两相流动微分方程这一难题。

2 汽液两相流动的瞬态方程

汽液两相流动的情况在很多换热设备中都能遇到,而且其流动情况非常复杂。所以在进行两相流动的有关计算时,就需要根据实际要求对其进行一定的简化,即将其看作是一维的管道流动。在许多文献中都可以查阅到一维管道两相流动的瞬态微分方程[6],但要实现多尺度小波数值解法,还必须对已知的方程式进行一定的推导,使多尺度小波数值解法能顺利地得以实现。下面将给出其推导过程和最终的离散方程。

首先由工质(水)物性得知,流体的密度应是压力和焓的函数,即 $\rho=f(p,h)$。因此密度对时间的导数可化为压力和焓对时间的导数:

$$\frac{\partial\rho}{\partial t}=\frac{\partial\rho}{\partial p}\cdot\frac{\partial p}{\partial t}+\frac{\partial\rho}{\partial h}\cdot\frac{\partial h}{\partial t} \tag{1}$$

进一步可得到:

$$\frac{\partial p}{\partial t}=\left(\frac{\partial\rho}{\partial t}-\frac{\partial\rho}{\partial h}\cdot\frac{\partial h}{\partial t}\right)\Big/\left(\frac{\partial\rho}{\partial p}\right) \tag{2}$$

对能量守恒方程式最终化为下面的形式,具体推导过程可参考文献[7]:

$$\rho''\frac{\partial h}{\partial t}+G\frac{\partial h}{\partial z}=\frac{q_l}{A}+\frac{\partial p}{\partial t} \tag{3}$$

其中:$G=\frac{W}{A}$, $\rho''=[\rho_f x+\rho_g(1-x)]\frac{d\alpha}{dx}$。

同样也要对动量守恒方程式进行推导使其变为类似于上面的能量守恒方程的形式。由于动量守恒方程焓有 W^2 项,在对其进行推导时可以看作 $W\times W$,这样就得到下面的形式:

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$$\frac{\partial W}{\partial t}+\frac{W}{\rho' A}\frac{\partial W}{\partial z}=-A\frac{\partial p}{\partial z}-\int_{U_\varepsilon}\tau_f\,\mathrm{d}l-\rho gA-W\frac{\partial}{\partial z}\left(\frac{W}{\rho' A}\right) \quad (4)$$

其中：$\rho'=1\Big/\left(\frac{(1-x)^2}{\rho_f(1-\alpha)}+\frac{x^2}{\rho_g\alpha}\right)$，

$\int_{U_\varepsilon}\tau_f\,\mathrm{d}l=\frac{fW\mid W\mid\Phi_{tp}^2}{2D_e\rho A^2}$。

将式(2)、式(3)和式(4)联立，并结合物性方程：

$$\begin{cases}\frac{\partial p}{\partial t}=\left(\frac{\partial\rho}{\partial t}-\frac{\partial\rho}{\partial h}\cdot\frac{\partial h}{\partial t}\right)\Big/\left(\frac{\partial\rho}{\partial p}\right)\\ \rho''\frac{\partial h}{\partial t}+G\frac{\partial h}{\partial z}=\frac{q_l}{A}+\frac{\partial p}{\partial t}\\ \frac{\partial W}{\partial t}+\frac{W}{\rho' A}\frac{\partial W}{\partial z}=-A\frac{\partial p}{\partial z}-\int_{U_\varepsilon}\tau_f\,\mathrm{d}l-\\ \rho gA-W\frac{\partial}{\partial z}\left(\frac{W}{\rho' A}\right)\\ \text{物性方程}\end{cases} \quad (5)$$

这时式(5)就可以形成一个封闭的方程组，在给定边界条件和初始值后就可对此方程组进行求解，计算出任意位置和任意时刻的流体的压力、焓以及流速等物理量。

3　小波数值离散结构的构造

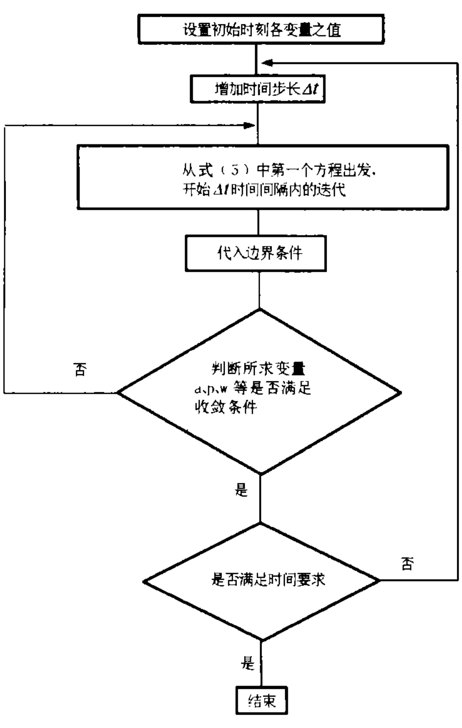

图 1　程序框图

在用小波数值方法对上述方程组求解之前还必须对它进行离散化。观察上面的方程组，可以看到它的每一单个方程都可以简化描述为：

$$C_1\frac{\partial\Phi}{\partial t}+C_2\frac{\partial\Phi}{\partial z}=C_3 \quad (6)$$

对式(6)的多尺度小波离散形式为：

$$(C_1^nD^0+C_2^n\Delta tD^1)\Phi^{n+1}=C_3^n\Delta t+C_1^n\Phi^n \quad (7)$$

其中 D^0, D^1 为小波导算子[6]；上标 n 表示物理量在第 n 时刻的值，同样 $n+1$ 表示物理量在第 n 时刻的下一时刻的值，略有不同的是在动量方程中，C_3^n 中的压力梯度应为第 $n+1$ 时刻的。完成对微分方程的离散后，式(5)中的任何一个方程都可以作为求解过程的开始，然后依次循环对其它方程进行求解，在又回到开始的方程时完成一轮迭代求解过程，接下来进行下一轮的迭代直到收敛为止，完成一个时刻的求解；再进行下一时刻的迭代求解，直到所要求的时间完成整个求解过程，程序框图见图 1。下面将用多尺度小波数值方法求解一个一维管道内的两相流动的瞬态过程，控制体的划分如图 2 所示，总共划分了 8 个控制体(cell)，输入的结构参数为：管道截面积为 0.000 3 m^2；管道直径为 0.02 m；沿管长均匀加热。

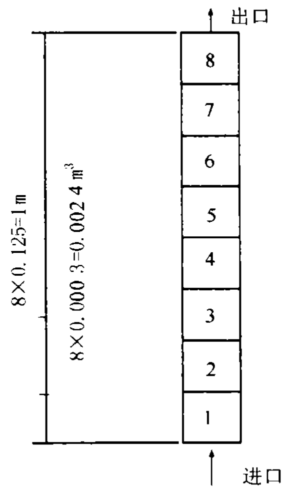

图 2　管道控制体的划分

4　算例与结果分析

在本例中所采用的一维管道汽液两相流动的结构及工质(水)热工参数如下：

(1) 沿管长均匀加热，线功率 0 kW/m；管长 1 m；管径 0.02 m；管道进口工质压力 10 MPa，管道进口工质过冷度 3.02 ℃，管道进口工质截面质量流速 3 000 kg/(m^2 · s)。

上面的流动情况为在 0 时刻以前的流体流动，即为一纯单相流动工况。下面的流动情况为在 0 时刻以后的流体流动，即给整个管道突然加上线功率为 188.5 kW/m 的热流，这时流体在流动时就有可能发生相变，出现汽液两相流动的情况，其过程将是一个从稳态的单相流动向汽液两相流动的新稳态工况

的瞬态转变过程。

(2) 沿管长均匀加热, 线功率 188.5 kW/m, 管长1 m 管, 管径 0.02 m, 管道进口工质压力 10 MPa, 管道进口工质过冷度 3.02 ℃, 管道进口工质截面质量流速3 000 kg/(m^2 · s)。

这里除了用作者自己开发的多尺度小波数值计算（在这里中取小波尺度 $J = 4$, 时间步长 $\Delta t = 0.01$ s）方法对此过程进行计算外, 还应用了一商用软件Mini—TRAC（是国际上通用的反应堆流体热工计算商用软件TRAC的微缩版本, 可以用于对新算法和模型的检验）对此过程进行计算, 并对两者的计算结果进行了比较(如图3～图8所示, 图中虚线为Mini—TRAC的计算结果, 实线为多尺度小波数值计算结果), 图中的结果是控制体中心处的流体计算值。

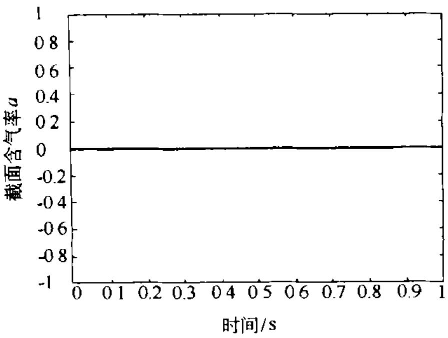

图 3　入口控制体的截面含气率

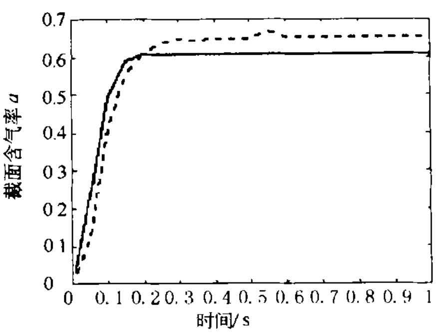

图 4　出口控制体的截面含气率

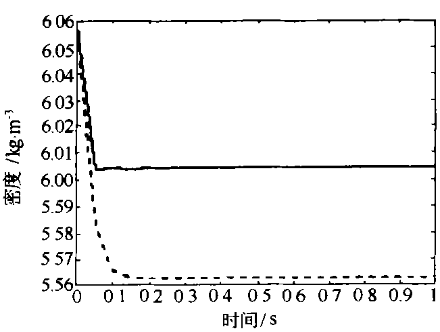

图 5　入口控制体的平均密度

图3 和图 4 示出了进口和出口控制体的含气率的小波和Mini—TRAC 的比较结果, 在入口控制体内 0 时刻前后均为单相液体, 因此含气率始终为 0, 从图中可知小波和Mini—TRAC 计算结果相同; 在出口控制体内, 含气率由 0 逐渐上升并达到一稳定值, 在此含气率的瞬态变化过程中, 小波数值结果始终与 Mini—TRAC 计算结果相吻合。为了对小波数值结果做一全面的验证, 还在图5和图6进行了进口和出口控制体的平均密度和在图7和图8的进口和出口控制体的平均速度的小波和Mini—TRAC的比较结果, 同样可以看到小波数值结果始终与Mini—TRAC计算结果相吻合, 并且误差不超过 ±5%。

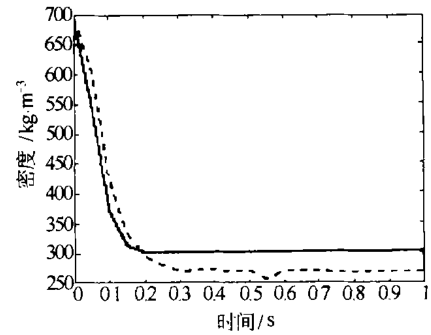

图 6　出口控制体的平均密度

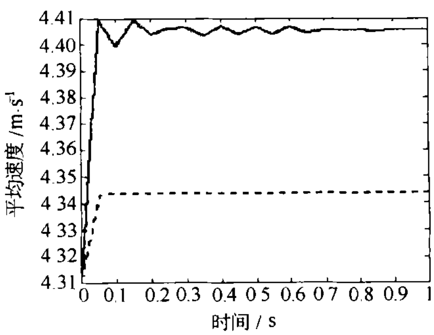

图 7　入口控制体的平均速度

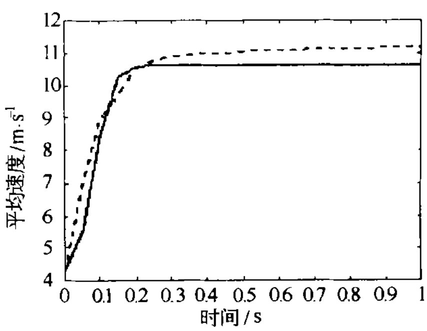

图 8　出口控制体的平均速度

5　结论

可以说多尺度小波数值方法对于存在相变的汽液两相流动能够给予较准确的计算, 并且其计算结果能够符合物理现象和物理规律。在这个瞬态计算过程中, 各参数不仅随空间在变化, 而且还随时间在变化, 这使得由这些参数生成的微分方程的系数项的变化同稳态情况相比, 变得更为复杂。这种情况将对数值计算的要求也变得更为苛刻, 不但要保证数值结果的空间收敛性, 而且更要防止它的时间发散。本文不仅将这种数值方法应用在瞬态耦合微分方程求解中, 而且还发现小波数值方法对于汽液两

相流动的瞬态计算是可靠和准确的。

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(辉 编辑)

传动装置

改进的 501 K 齿轮箱

据《Gas Turbine World》2001 年 7—8 月号报道, 501—KB5 是一型用于电力生产的燃气轮机装置, ISO 条件下基本负荷额定功率为 3 931 kW、热效率为 28.8%。自 1982 年推出该型燃机以来, 现在已发展成包括 501—KB5S、501—KB7、501—KH5, 功率从 3 949 kW 到 6 420 kW 的整个系列燃机。

自从 501K 型燃机面世以来, 英国 Allen 齿轮公司已为该型燃机承包商 Centrax、Turbomeca 和 Rolls—Royce 公司制造并交付了 270 多台减速齿轮箱。

这些齿轮箱使 501K 上的 14 200 r/min 燃气轮机输出轴转速降低到同步转速, 以便驱动用于 50 Hz 或 60 Hz 电力生产的发电机。

周转行星齿轮布置节省费用和空间。它取消了内部连接环, 减少了齿轮组的外径并允许使用更小的齿轮箱。

周转齿轮箱设计成安装在发电机上, 用螺栓把齿轮箱直接安装在发电机端盖上, 从而比平行轴布置更紧凑和更轻。

Allen 齿轮公司声称, 它最近重新设计了齿轮箱, 以便更容易接近内部方便日常维护。

重新设计包括改变安装支架在起动机传动装置上的布置以及润滑油泵惰轮组件的布置。

(思娟 供稿)

fication Heat-transfer Tube Incorporating an Electric Field and Spiral Coils [刊, 汉] / LIU Zhen-hua, YI Jie (Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). —475 ~477

An experimental study of combined-intensification heat transfer was conducted by using two intensification techniques to the laminar flow heat transfer of in-tube oil, namely, the installation of internally inserted spiral coils and an externally added high-voltage electric field. The result of the experiment indicates that the intensification tube with the use of internally inserted spiral coils can lead to an enhancement of convection heat transfer of the laminar flow by about 100%. The use of intensified heat exchange with the help of a high-voltage electric field in addition to the above approach can further enhance the heat exchange intensification rate by about four times. Oil temperature and its flow speed do not exert any significant influence on the heat exchange intensification rate. The heat exchange intensification rate basically depends on the externally applied high-voltage electric field. **Key words**: convection heat transfer, combined intensification of heat exchange, electro-hydrodynamics

梯形剖面圆形肋片管温度场的研究 = **A Study of the Temperature Field of Annular Finned Tubes with a Trapezoidal Cross-section** [刊, 汉] / LU Guo-dong, ZHOU Qiang-tai (Power Engineering Department, Southeastern University, Nanjing, China, Post Code: 210096), CHENG Lin, TIAN Mao-cheng (School of Energy & Power Engineering under the Shandong University, Jinan, China, Post Code: 250061) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). —478 ~480

A new method is proposed for calculating the temperature distribution along the fin height (i.e., along the fin-root to fin-end direction) of an annular finned tube with a trapezoidal cross-section. Measurement results indicate that the proposed calculation method features a fairly high precision. Meanwhile, a non-uniform distribution of temperature was identified along the fin-width direction (namely, along the fin thickness direction), which is of major reference value for the structure optimization of annular fins. **Key words**: finned tube, temperature field, heat transfer characteristics, structure optimization

高温鼓泡流化床的流化行为 = **Fluidization Behavior of a High-temperature Bubbling Fluidized Bed** [刊, 汉] / GUO Qing-jie, LU Jun-fu, WANG Xin, et al (Department of Thermal Engineering, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy &Power. — 2002, 17(5). —481 ~484

With the bed temperature ranging from 20 - 1000 ℃ and coal ash of four kinds of particle diameter serving as experimental materials the variation relationship of the following parameters is investigated under various apparent gas speeds. The parameters include: the minimum fluidization speed, bed average voidage, pressure fluctuation standard deviation and main frequencies. The minimum fluidization speed will decrease with a rise in bed temperature. Under the same bed temperature the average voidage will increase with a rise in apparent gas speed. Under different temperatures the pressure fluctuation deviation will experience an increase with an increase in fluidization number. Under the same fluidization number the influence exerted by a change in bed temperature on pressure fluctuation standard deviation of B particles is insignificant, while for particles of D category the pressure fluctuation standard deviation will decrease with a rise in bed temperature. An increase in fluidization number will lead to a decrease in the main frequency of pressure fluctuations. **Key words**: fluidized bed, high temperature, minimum fluidization speed, pressure fluctuation deviation

一维管道汽液两相流动的小波数值瞬态计算 = **Transient Calculation by a Wavelet Numerical Method for a One-dimensional Piping of Vapor-liquid Two-phase Flows** [刊, 汉] / SHANG Zhi, YANG Rui-chang (Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy &Power. — 2002, 17

(5). —485～488

Wavelet analysis represents a new tool of mathematical analysis. The use of this numerical calculation method for the transient thermodynamic calculation and analysis of vapor-liquid two-phase flows is of major practical significance. The comparison of the transient calculation results of vapor-liquid two-phase flows by a wavelet numerical method with those of Mini-TRAC calculation method has shown that the wavelet numerical method is fully suited to perform the transient calculation of coupled differential equations for vapor-liquid two-phase flows. **Key words**: wavelet analysis, numerical calculation, vapor-liquid two-phase flow

现场测试地下岩土平均热物性参数方法＝**A Method for the On-site Testing of Average Thermo-physical Parameters of Underground Rock Soil** [刊, 汉] / YU Ming-zhi, FANG Zhao-hong (Shandong Architectural Engineering Institute, Jinan, China, Post Code: 250014) //Journal of Engineering for Thermal Energy &Power. — 2002, 17(5). —489～492

The magnitude of average thermo-physical parameters exerts a significant influence on the number and depth of holes to be drilled, thus affecting the capital investment outlays for a ground-source heat-pump system. To realize the on-site measurement of the average thermo-physical parameters of underground rock soil, a set of on-site measuring equipment was put into use. With its help measurements were taken of the heat flow an underground embedded pipe loop is subjected to and of the temperature change of the circulating water in the loop with the passage of time. Moreover, a piece of software developed by the authors was utilized to calculate and determine the average thermo-physical parameters of the underground rock soil by using a parameter-evaluation method. **Key words**: geothermal heat exchanger, average thermo-physical parameter of rock soil, measuring method

多背压凝汽器的平均冷凝温度＝**The Mean Condensation Temperature of a Multi-pressure Condenser** [刊, 汉] / XU Zhi-ming, YANG Shan-rang, LUO Zhen, et al (Northeast Institute of Electric Power Engineering, Jilin, China, Post Code: 132012) //Journal of Engineering for Thermal Energy &Power. — 2002, 17(5). —493～495

Through a theoretical analysis the authors have derived a relationship for calculating the mean condensation temperature of a multi-pressure condenser, which has taken into account the variation of heat transfer factor with the change of condenser construction scheme and cooling water inlet temperature. Analyzed is the influence of the heat transfer area and the circulation ratio of various stages on the mean condensation temperature. Moreover, with the mean condensation temperature of the multi-pressure condenser serving as a target function an optimized construction of the condenser has been worked out. **Key words**: multi-pressure condenser, condensation temperature, circulation ratio, optimization

大型火电机组表面式加热器动态数学模型研究与开发＝**Research and Development of a Mathematical Model for the Surface Heater of a Large-sized Thermal Power Plant** [刊, 汉] / WANG Jian-mei, LIU Guang-lin, CAI Kai, et al (Wuhan University, Wuhan, China, Post Code: 430072) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). —496～498

With a simulation supporting system STAR-90 serving as a platform developed is a fairly accurate mathematical model to study a regenerative heating system. The model is capable of not only meeting a given static precision, but also accurately reflecting and reproducing the major features of various operating conditions of a specific regenerative heating system. Furthermore, it is also feasible to employ the above mathematical model for the research of certain dynamic characteristics of heaters. **Key words**: heater, mathematical model, dynamic characteristics, regenerative heating system