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往返式冷凝器中流场数值模拟的研究

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摘 要:倾斜往返式冷凝器采用冷凝回流的方式来完成蒸汽的冷凝过程,本文在试验的基础上,采用两流体分析模型,建立了往返式冷凝器内蒸汽冷凝回流的流动分析模型,编制开发了相应的Matlab计算程序,并根据试验测得的初值条件,对其流场进行了数值模拟,并对计算结果进行了分析。结果表明,截面汽相所占有的份额沿管长方向逐渐增大;汽液两相流速沿管长方向逐渐减小;在相同压力下,当倾角 $\beta=90°$ 时,液膜最薄,两相流速沿管长的变化最为显著;当倾角一定时,随着压力减小,液膜厚度也逐渐减小。

关 键 词:往返式冷凝器;冷凝回流;流场

中图分类号:TK264;O24 文献标识码:A

符号说明

A— 流通截面积/m^2;
d— 管内径/m;
α— 截面上汽相占有的份额;
g— 重力加速度/$m\cdot s^{-2}$;
ρ— 密度/$kg\cdot m^{-3}$
p— 压强/$N\cdot m^{-2}$;
U— 润湿周长/m;
m— 质量流量/$kg\cdot s^{-1}$;
r— 汽化潜热/$J\cdot kg^{-1}$;
μ—动力粘度/$kg\cdot(m\cdot s)^{-1}$;
R— 管内半径/m;
f— 摩擦力系数;
τ— 切向应力/$N\cdot m^{-2}$;
β— 倾角;
α_x— 局部换热系数/$W\cdot m^{-2}\cdot ℃^{-1}$;
e— 单位质量介质含有的能量/$J\cdot kg^{-1}$。

下 标

g— 汽相;
l— 液相;
i— 汽液界面;
w— 管壁。

1 引 言

倾斜往返式冷凝器在应用中采用冷凝回流的方式完成蒸汽冷凝过程,采用这种形式的冷凝器可使冷凝液的温度差不多处于沸点温度,不但可以起到节能的作用,而且也可以满足某些生产工艺的要求[1]。但在应用中当蒸汽流速增大到某一数值时,由于冷凝液受到壁面剪切应力和汽液交界面上汽相切应力的作用,液膜开始变得不稳定,出现大幅度的波动,此时,在液膜的波峰处不断有液滴脱落,被蒸汽携带着向上流动,这些液滴离散在汽流中心部,同时也有一些液滴又沉积到液膜中,从而使该处的液膜厚度增加,管内的蒸汽质量流量和冷凝液的质量流量出现不平衡,管内有液体堆积。当蒸汽的流速进一步增大时,管内的冷凝液将不再向下流动而出现液阻现象,液阻的出现将对冷凝器特别是核电站的冷凝器的安全运行构成极大的威胁。因此对液阻的研究一直是广大科技工作者极为关注的课题之一[2~5]。通过对其流场的研究,可以更加深刻的了解液阻现象,以便于求得精度更高的液阻关系式,但是由于其控制方程的复杂性,获得解析解几乎是不可能的。随着计算机技术的发展和计算方法的改进,数值模拟以其独有优点在许多领域得到了广泛的重视和应用,但目前应用数值模拟的方法来研究倾斜往返式冷凝器中流场的工作做的还很少。本文在试验的基础上,采用数值模拟的方法对其液阻发生前一瞬间的流场进行了模拟和分析。

2 物理数学模型的建立

试验装置和试验过程可见文献[6],物理模型如图1所示。处于饱和温度 t_s 的蒸汽以速度 u_{g0} 从半径为 R 的冷凝器的下端进入,蒸汽和冷凝液相接触,边流动边被冷凝,冷凝液受到重力、汽液界面剪切力和壁面粘滞力的共同作用沿管壁自然向下流动。假定:(1)常物性;(2)汽液界面平整无波动;(3)蒸汽和冷凝液均处于饱和态;(4)汽液界面上无温差;(5)忽略液膜的过冷度;(6)流动处于平衡状态;(7)介质的宏观动能和势能均忽略不计。则相应的控制方程为:

质量守恒方程:

$$\frac{d[\rho_l u_l(1-\alpha)]}{dx}+\frac{d(\rho_g u_g \alpha)}{dx}=0 \qquad (1)$$

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动量守恒方程:

$$\frac{d[\rho_1 u_1^2(1-a)]}{dx}+\frac{d(\rho_g a u_g^2)}{dx}=-\frac{dp}{dx}-\rho_1\times$$

$$(1-a)g\sin\beta-\rho_g a g\sin\beta+\frac{\tau_w U_w}{A} \quad (2)$$

能量守恒方程:

$$\frac{d[\rho_1(1-a)u_1 e_1]}{dx}+\frac{d(\rho_g a u_g e_g)}{dx}+\frac{a_x \Delta t U_w}{A}=0 \quad (3)$$

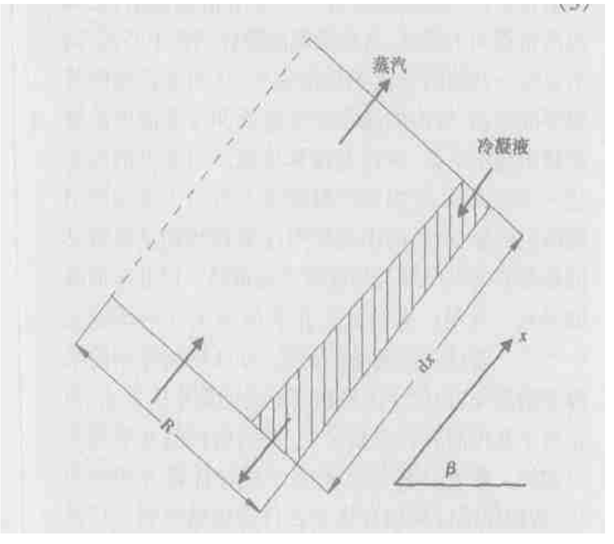

图 1 往返式冷凝器冷凝回流物理模型

3 结构方程的建立

观察以上控制方程可以看出, 未知数的个数多于控制方程的个数, 方程组不封闭, 需要补充有关的结构方程使其封闭才能求解。

3.1 压强降

控制方程中的压强降应该有 3 部分组成[7~8]:

(1) 重力压强降是静压强梯度:

$$(dP/dx)_g=-\rho_g g$$

(2) 摩擦压强降是由汽液界面切应力产生的压强梯度:

$$(dP/dx)_f=2\tau_i/(R-\delta)$$

(3) 惯性压强降是由于产生加速度而引起的压强降:

$$(dP/dx)_m=\rho_g(du_g^2/dx)$$

因此有:

$$dP/dx=-\rho_g g+\frac{2\tau_i}{R-\delta}+\rho_g\frac{du_g^2}{dx} \quad (4)$$

汽液界面切应力 τ_i 的求取:

根据文献[8] 可知:

$$\tau_i=f_i\frac{\rho_g}{2}(u_g-u_1)^2+\frac{\lambda_1(T_s-T_w)}{\alpha_x\delta}(u_g-u_1) \quad (5)$$

式中: f_i 与雷诺数 $Re_g=\dfrac{4m_g}{\pi(d-2\delta)\mu_g}$ 有关:

$Re_g<2\,000$ 时, $f_i=16/Re_g$;

$2\,000<Re_g<4\,000$ 时, $f_i=Re_g^{0.33}/1\,525$;

$Re_g>4\,000$ 时, $f_i=0.08/Re_g$。

3.2 τ_w 及 α_x 的求取

壁面切应力 τ_w 的求取[9]:

$$\tau_w=\frac{f_1}{8}\rho_1 u_1^2 \quad (6)$$

式中: f_1 与液相的雷诺数 $Re_1=\dfrac{(1-\alpha)d\rho_1 u_1}{r_1}$ 有关:

$Re_1<2\,320$ 时, $f_i=\dfrac{64}{Re_1}$;

$4\,000<Re_1<26.98\left(\dfrac{d}{\varepsilon}\right)^{\frac{7}{8}}$ 时, $f_i=\dfrac{0.316\,4}{Re_1^{0.25}}$。

当 $2\,320<Re_1<4\,000$ 时, 可用插值法求得, 在计算中一般 $Re_1<2\,320$, 液相的流动处于层流区。

根据纯液膜导热理论可得:

$$\alpha_x=\lambda_1/R\ln\left(\frac{R}{R-\delta}\right) \quad (7)$$

4 数值计算与结果分析

计算前, 先对原控制方程组处理, 主要是以下两方面的工作: (1) 消掉未知数 u_1, 以减少由于两相流动方向相反引起的离散和编程上的麻烦; (2) 方程的无量纲化处理。

由于在液阻发生前的任一时刻在任一截面上, 汽相和液相的质量流量均相等且流动方向相反, 故对式(1) 积分可得:

$$\rho_1 u_1(1-\alpha)+\rho_g u_g\alpha=0 \quad (8)$$

由式(8) 求得 u_1 代入式(2) 和式(3) 便可消去未知数 u_1。其计算结果如图 2 ~ 图 7 所示。

图 2 ~ 图 4 示出了在压力 $p=1.0\times10^5$ Pa 时不同倾斜角度下截面汽相占有的份额、无量纲汽相速度和无量纲液相速度沿管长的分布。从图中可以看出, 在所有倾角下 α 沿管长方向均逐渐增大, 随着倾角的不同其增大的幅度变化不大, 在倾角 β = 90° 时, 其增大的幅度最大, 液膜最薄。在管子的进汽端, 其液膜厚度随着倾角的变小而减小。无量纲汽相速度和无量纲液相速度均沿着管长方向逐渐减小, 在实际的冷凝器中, 到达管子的末端时, 其各相的流速

应都为零, 由于在本试验中, 冷凝管所受到的冷凝能力不够大, 在管子的末端, 两相流速都未减小到零。未被冷凝的蒸汽在附加冷凝器中被冷凝为水后, 沿管壁流下来。从图中也可以看出, 随着倾角的不同, 其流速的减小幅度也不相同, 在倾角为 90° 时, 减小程度最为显著。

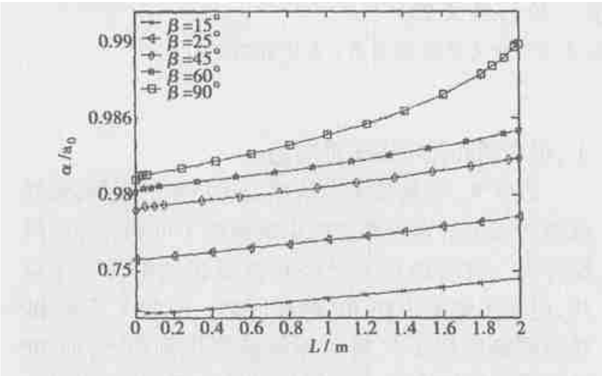

图 2　$p = 1.0\times 10^5$ 时, 不同倾角下 α 沿管长的分布

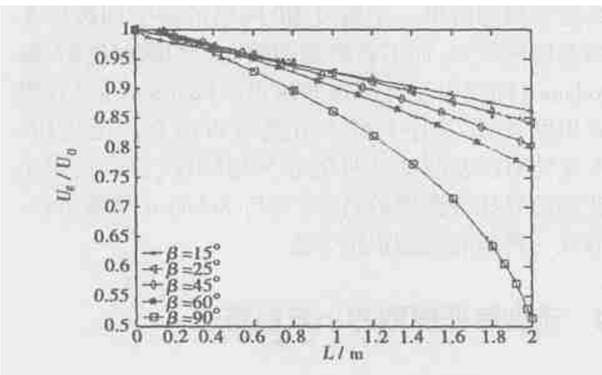

图 3　$p = 1.0\times 10^5$ 时, 不同倾角下 u_g 沿管长的分布

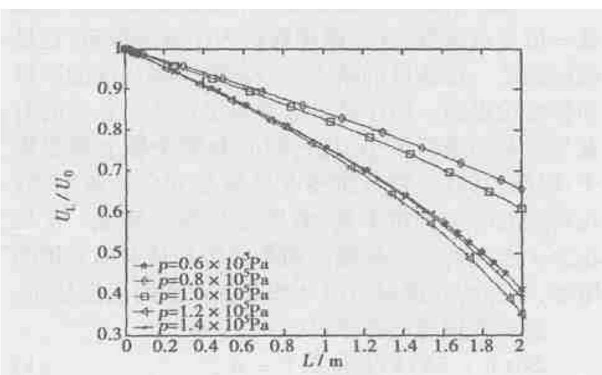

图 4　$p = 1.0\times 10^5$ 时, 不同倾角下 u_l 沿管长的分布

图 5 ~ 图 7 示出了倾角为 90° 时在不同的压力下截面汽相占有的份额、无量纲汽相速度和无量纲液相速度沿管长的分布。从图中可以看出, 在压力 $p = 0.6\times 10^5$ Pa 时, 液膜最薄。压力较小时, 液膜厚度的变化幅度较大; 而压力较大时, 液膜厚度的变化幅度较小。无量纲汽相速度和无量纲液相速度也沿着管长方向逐渐减小, 由于同样的原因, 在管子的末端, 两相流速都未减小到零。随着压力的增大, 两相流速沿管长的减小幅度均增大, 当压力 $p = 1.2\times 10^5$ Pa 时, 减小的幅度最大。

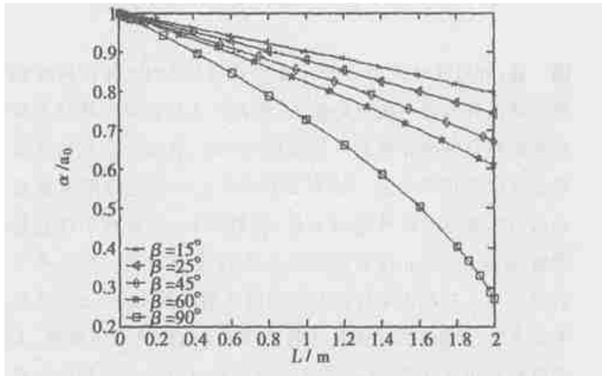

图 5　β = 90° 时, 不同压力下 α 沿管长的分布

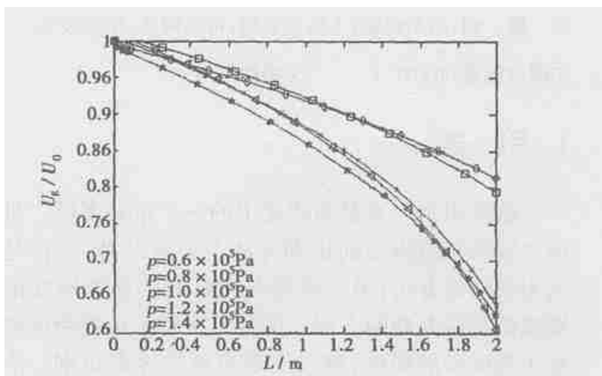

图 6　β = 90° 时, 不同压力下 u_g 沿管长的分布

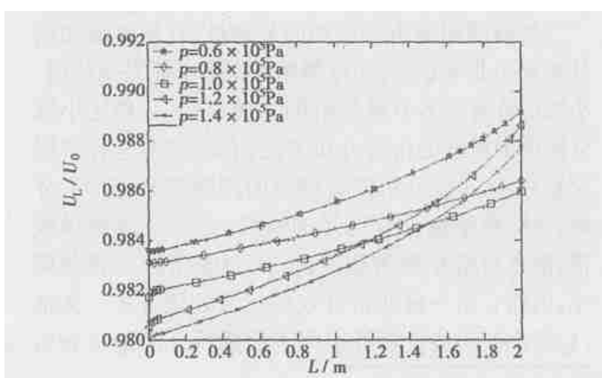

图 7　β = 90° 时, 不同压力下 u_l 沿管长的分布

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统。该系统能对锅炉汽包运行全过程实行温度、压力和寿命的管理,并指导锅炉运行。

(2) 开发的汽包疲劳寿命在线监测系统运行稳定,各项数据准确可靠。系统启动以后,即可自行完成采集、判断、计算和报警等各项功能,自动化程度高。

(3) 本系统所选用的开发平台为 Delphi 7.0。它采用了弹性可重复利用的完整的面向对象程序语言和当今世界上最快的编辑器和最为领先的数据库技术。因而该系统软件先进,易于推广和进行二次开发。

(4) 通过对 300 MW 机组锅炉汽包应力场的三维有限元计算,得到了汽包在内压作用下的理论应力集中系数,计算结果比德国《蒸汽锅炉技术规程》(TRD301)标准推荐的理论应力集中系数大 17.3%。并以有限元计算结果代替 TRD301 推荐的理论应力集中系数,再计算汽包疲劳寿命,这样的处理偏于安全。在对其它类型电厂锅炉进行疲劳寿命分析时,建议应力集中系数的选取应以有限元计算结果为准。

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5 结 论

本文结合倾斜式冷凝器冷凝回流的试验,建立了相应的数学模型,并根据试验测得的数据结果,采用数值模拟的方法,获得了在不同参数下,截面汽相所占有的份额和汽液两相流速沿管长方向上的分布,并得到了一些有价值的结论。

(1) 截面汽相所占有的份额沿管长方向逐渐增大,冷凝能力足够大时,在冷凝器的末端 $\alpha=1$;

(2) 汽液两相流速沿管长方向逐渐减小,冷凝能力足够大时,在冷凝器的末端应为零;

(3) 在同一压力下,当倾角 $\beta=90^{\circ}$ 时,液膜最薄,两相流速沿管长的变化最为显著;

(4) 在同一倾角 $\beta=90^{\circ}$ 下,随着压力的减小,液膜厚度也逐渐减小。

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object. Through an exposition of neural network discrimination and modeling principle the authors have by an analysis of power plant on-site data set up respectively a linear mathematical model of steam-drum water level relative to feedwater flow rate and a nonlinear model of superheated steam temperature relative to specific value β. As the neural network-based modeling can result in high computation speed and precision, the model output basically reflects the actual operating conditions of the thermotechnical object. **Key words**: thermotechnical object, neural network, on-site data, dynamic modeling, simulation

电厂热力系统的长期动态特性模型＝**Long-term Dynamic Characteristics Model of a Power Plant Thermodynamic System** [刊, 汉] / LI Yun-ze, WANG Jun (College of Aeronautical Science &Engineering under the Beijing University of Astronautics and Aeronautics, Beijing, China,, Post Code: 100083), YANG Xian-yong (Department of Thermal Energy Engineering, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy &Power. — 2004, 19(2). —38～40, 44

The long-term dynamic characteristics of a thermodynamic system are of major significance to the design of simulation or control systems for various types of thermal power plants. Through a rational analysis and simplification of relevant mechanism a mathematical model of long-term dynamic processes has been set up for a thermodynamic system from an integral standpoint. Such an integral dynamic model can fairly rationally reflect the heat accumulation and work-performing law of the thermodynamic system in a long-term dynamic process. As a result, the above model can remedy the deficiency of the dynamic model of present-day thermal power plants and better meet the requirements for analyzing plant long-term dynamic characteristics and studying plant load control strategy. With the model serving as a tool a simulation study was conducted of the long-term dynamic characteristics of a 600 MW supercritical power plant. The simulation results have been found to be rational and accurate. **Key words**: power plant thermodynamic system, long-term dynamic characteristics, dynamic thermal balance, mathematical model

底部加直管旋风分离器的性能预测＝**Performance Prediction for a Cyclone Separator with an Added Vertical Pipe at Its Bottom** [刊, 汉] / QIAN Fu-ping, ZHANG Ming-yao (Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology under the Research Institute of Thermal Energy Engineering and Southeastern University, Nanjing, China, Post Code: 210096) //Journal of Engineering for Thermal Energy &Power. — 2004, 19(2). —41～44

To cope with the problem of "the re-entrainment into the hopper of fine dust particles in an inner vortex flow due to the agitation of separated particles" occurring in conventional cyclone separators, some researchers have proposed the adding of a straight pipe at the bottom of the separator, thereby allowing dust-laden air to enter the pipe for further separation. By using a Reynolds Stress Transportation Model (RSTM) a numerical simulation was conducted of the internal gas-phase flow field in a conventional cyclone separator and in a cyclone separator with an added straight pipe at its bottom. Furthermore, an analysis was performed of the downward flow at the cone bottom of the conventional cyclone separator. The results of the analysis indicate that the gas flow eddying at the cone bottom of the conventional cyclone separator is found to be still very intense and its downward flow does not amount to zero. On the other hand, the cyclone separator with an added straight pipe has made its tail vortex stagnating in the straight pipe. This has led to the provision of an additional separation space for ash dust, creating a favorable condition for its further separation. **Key words**: cyclone separator, straight pipe, Reynolds stress transportation model, numerical simulation

往返式冷凝器中流场数值模拟的研究＝**A Study of the Numerical Simulation of Flow Field in a Reciprocating**

Condenser [刊，汉] / FENG Ming-jie，CHEN Wen-zhong (Institute of Materials and Metallurgy under the Northeastern University，Shenyang，China，Post Code：110006) //Journal of Engineering for Thermal Energy &Power. — 2005，20(1). —45～47，60

By adopting a form of condensate return flow an inclined reciprocating condenser completes its steam condensation process. On the basis of tests and by using a two-phase fluid analytical model set up was a flow analysis model for steam-condensate return flow in a reciprocating condenser. A corresponding Matlab computation program was prepared and developed. Moreover，on the basis of the condition of initial values measured and obtained from the tests a numerical simulation was conducted of the relevant flow field along with an analysis of the computation results. The results of the analysis indicate that the share occupied by the cross-section steam phase gradually increases along the tube length direction. Steam-liquid two-phase flow speed decreases gradually along the tube length direction. Under an identical pressure when inclination angle β equals 90°，a liquid film will have the thinnest value，and the variation of the two-phase flow speed along the tube length becomes very conspicuous. With the inclination angle β being 90° the liquid film thickness will gradually decrease with a decrease in pressure. **Key words**：reciprocating condenser，condensate return flow，flow field

基于小波包分解和 Kohonen 神经网络的气液两相流流型识别方法＝**A Method for Identifying Gas-liquid Two-phase Flow Patterns on the Basis of a Wavelet Packet Decomposition and Kohonen Neural Network** [刊，汉] / SUN Bin (Power Engineering Department，North China University of Electric Power，Baoding，China，Post Code：071003)，ZHOU Yun-long，ZHANG Ling，et al (Power Engineering Department，Northeastern Institute of Electric Power，Jilin，China，Post Code：132012) //Journal of Engineering for Thermal Energy &Power. — 2005，20(1). —48～51

The traditional method of flow pattern identification suffers from the deficiency of a high subjectivity and BP neural network training is relatively seriously affected by a sickly sample. In view of the above，the authors have，on the basis of the fact that the transformation of a wavelet packet can decompose signals according to arbitrary time-frequency resolution rate into characteristics of different frequency sections，proposed a new method for identifying gas-liquid two-phase flow patterns. Firstly，the method analyzes the dynamic pressure-difference fluctuation signals of a flow pattern by utilizing wavelet packet decomposition and extracts the characteristics. Then，by combining wavelet-packet energy specific features with Kohonen neural network，flow pattern identification can be performed. The successful identification of four typical flow patterns of air-water two-phase flow in a horizontal pipe has shown that the recommended method can effectively overcome the above-mentioned deficiency of the traditional identification method，thus providing a new and highly effective technical alternative for the on-line identification of flow patterns. **Key words**：flow pattern identification，wavelet packet decomposition，neural network，pressure-difference fluctuation

热电(冷)联产系统的优化性能 *＝**Optimized Performance of a Combined Heat and Electric Power (Cooling) System** [刊，汉] / ZHANG Xiao-hui，YANG Mo (College of Power Engineering under the Shanghai University of Science &Technology，Shanghai，China，Post Code：200093) //Journal of Engineering for Thermal Energy &Power. — 2005，20(1). —52～56

On the basis of a finite-time thermodynamics theory a basic optimization relationship is derived when an irreversible combined heat and electric power system as well as a combined heat and electric power (cooling) system have both attained a maximum system output. The scope of selecting optimized parameters and optimized configuration has been determined for the combined heat，electric power (cooling) system. Characteristics of optimized matching of heat supply (refrigeration) and electric power generation have also been obtained. Through numerical calculation examples identified was the