热 力 工 程

文章编号: 1001－2060(2008)02－0157－04

螺旋肋片自支撑换热器强化换热试验研究

吴金星, 朱登亮, 魏新利, 曹玉春
(郑州大学 节能技术研究中心, 河南 郑州 450001)

摘 要: 为了利用螺旋流动强化传热的特性并简化换热器结构, 结合螺旋折流板换热器的结构和流体流动特点, 开发了一种螺旋肋片自支撑换热器。为了掌握螺旋肋片自支撑换热器的传热和压降综合性能, 建立了换热器的试验模型和试验装置。在相同的试验条件下与折流杆换热器进行对比试验, 结果表明: 当雷诺数 Re= 6 000 时螺旋肋片换热器的总传热系数比折流杆换热器提高 13.3%, 并随着雷诺数增大强化传热效果更加显著; 而同时压力梯度却降低了 87.5%, 并随雷诺数增大二者的压力梯度差值变大。在试验雷诺数 2 000～6 500的范围内, 螺旋肋片换热器的综合性能 $K/\nabla P$ 值是折流杆换热器的 1.4～2 倍。可见, 螺旋肋片换热器具有较高的传热系数和较低的压降, 因而具有良好的发展及应用前景。

关 键 词: 螺旋肋片; 管壳式换热器; 自支撑; 折流杆; 强化换热

中图分类号: TK124, TQ051 文献标识码: A

引 言

随着常规能源的日益短缺, 节能降耗越来越受到人们的重视。换热器在能源动力和石油化工等行业是调节工艺介质温度和回收余热从而实现节能降耗的主要设备, 换热器的强化传热是提高换热器效率的重要措施。美国菲利普公司开发的折流杆换热器比传统的弓形折流板换热器大大降低了壳程流阻[1], 并在高雷诺数时获得了较好的强化壳程传热效果。继而国内也开展了高效低流阻纵流式换热器的相关研究[2], 不仅开发出用于正方形布管的折流栅结构, 严良文等人还开发出波形折流杆换热器专利产品[3], 可用于对三角形布管的折流板换热器进行改造, 在一定雷诺数范围内获得了良好效果。螺旋形折流板是近年来国内外开发的新型壳程强化传热结构[4～7], 它克服了弓形折流板支撑管束时具有阻力大、死角多、易积垢、易诱发管束振动等缺陷, 因而受到人们越来越多的重视。但螺旋形折流板比现有的多数管束支撑结构更复杂, 螺旋折流板和定距管的加工难度较大, 需要专用的加工胎具, 螺旋形折流板换热器的价格也高于弓形折流板换热器, 这在一定程度上限制了它的推广应用。为此, 东南大学梅娜等人提出了一种螺旋折流片管壳式换热器[8～9], 并对其套管换热器进行了数值模拟研究, 从而证实了该换热器中螺旋折流片能诱导流体做螺旋流动, 产生大量的涡流, 促进流体微团混合, 能有效地提高对流传热系数。

1 螺旋肋片自支撑管壳式换热器

为了利用螺旋流动强化传热的优点, 而又简化结构以便于加工和安装, 本文结合螺旋折流板换热器和螺旋折流片管壳式换热器的结构和流体流动特点, 提出了一种螺旋肋片自支撑管壳式换热器(以下简称“螺旋肋片换热器”)。该换热器采用了把管束支撑结构“化整为零”的简化思想, 把制造难度较大的整体式螺旋折流板简化为制造相对容易的围绕单根换热管的螺旋肋片, 从而将流体在壳程总体的螺旋流动变为围绕每根换热管的局部螺旋流动, 相邻换热管之间的旋转流体又相互干扰, 使流体产生新的掺混。螺旋肋片换热器不同于螺旋折流片换热器之处在于: 螺旋肋片的高度较小, 正好等于换热管的间距, 全部换热管都缠绕了螺旋肋片, 且同向布置。图 1 是螺旋肋片换热管束示意图和单根换热管照片。

在螺旋肋片换热器中, 螺旋肋片还起到支撑管束和保持管间距的作用, 不需要折流板。螺旋肋片的主要参数包括: 换热管外径 d, 螺旋肋片宽度 h, 螺旋肋片绕换热管旋转 360° 的长度, 即一个周期长度 H, 螺旋肋片的螺旋角 α 定义为螺旋肋片根部(即换热管表面)的螺旋线与换热管轴线的夹角, 即 $\alpha=\arctan(\pi d/H)$。

收稿日期: 2007－02－07; 修订日期: 2007－04－11

作者简介: 吴金星(1968－), 男, 河南通许人, 郑州大学副教授。

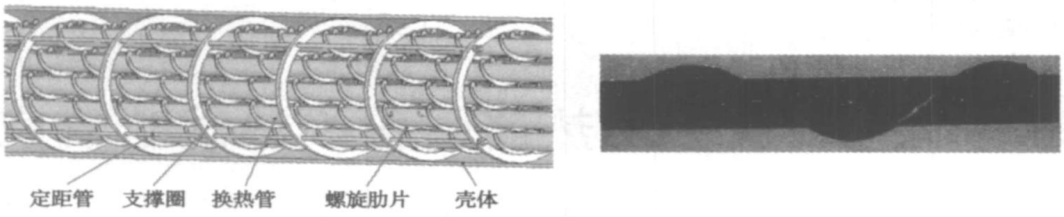


图 1 螺旋肋片换热器管束示意图及螺旋肋片管照片

对于大型螺旋肋片换热器，为了充分利用螺旋肋片的扰流作用，也为了便于螺旋肋片的加工，换热管全部采用旋向相同的螺旋肋片；安装时换热管之间完全靠螺旋肋片支撑和定位，不需要安装折流板，螺旋肋片也不会发生碰撞；组装时可先把支撑圈、管板、拉杆和定距管组装好，然后再穿换热管，支撑圈一方面对管束起支撑和定位的作用，另一方面阻止流体在管束与壳体之间的泄漏。与大型螺旋折流板换热器相比，螺旋肋片换热器结构简单，加工方便，适合大规模工业生产。

在螺旋肋片换热器壳程中，由于没有折流板，壳程流体在总体上沿管轴线呈纵向流动，螺旋肋片既对其所在区域内的流体产生影响，又会影响到周围流体，因此，壳程中的流体流动和传热状况十分复杂。在每根管子周围，流体受螺旋肋片的影响绕管轴线均呈螺旋流动；在相邻 3 ~4 根管子围成的流道中，流体一方面沿轴向流动，同时受周围的 4 根螺旋肋片的影响，使流体产生一定的螺旋流动。总的来说，螺旋肋片起到了两种较好的强化传热作用：(1)流体的有效流程加长，在相同的质量流量下，流速提高；(2)螺旋流动导致涡旋和二次流。流体的流速提高后，壁面附近的剪应力增大，边界层减薄，传热得以强化。做螺旋流动的流体受离心作用的影响，流体有径向速度分量，流体径向流动的结果是造成涡旋和二次流，促进了主流流体和壁面边界层流体充分混合，减薄了边界层，提高了传热系数，但流程的增长和湍流度的增加必然会带来压降的增大。

2 换热器试验装置与试验方法

为了测试螺旋肋片换热器传热和压降综合性能，建立了螺旋肋片换热器试验模型和试验装置，如图 2 所示。为了与工程应用较好的折流杆换热器对比，制造了一台折流杆换热器试验模型，其主要结构参数如壳体内径、换热管规格、换热管长度和数量、管中心距、排列方式等与螺旋肋片换热器完全相同。

两种换热器在相同的试验条件和同一传热试验平台上进行试验，试验平台由水蒸气和空气供料系统、数据采集与处理系统及换热器试验模型三部分组成，试验流程如图 3 所示。供料系统供应壳程和管程物料，包括燃油锅炉连续输送蒸汽至管程，鼓风机连续输送空气至壳程；数据采集系统由温度、压力、流量传感器、显示仪表、数据采集器、计算机等组成。

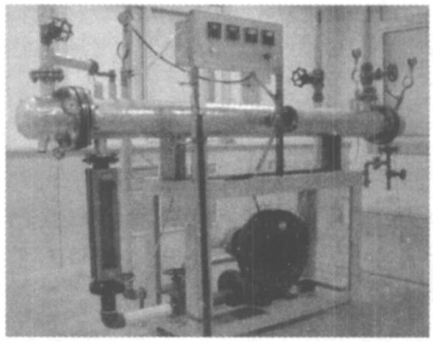


图 2 试验装置

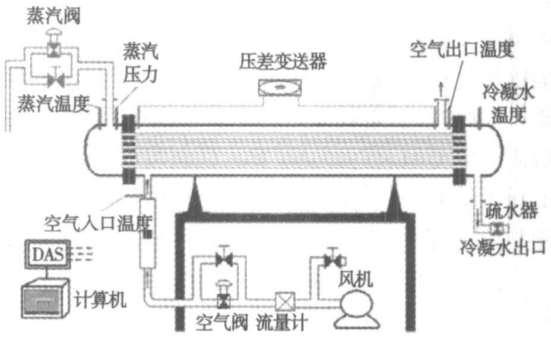


图 3 试验流程示意图

3 试验结果及其分析

图 4 为螺旋肋片换热器和折流杆换热器的总传热系数 K 随雷诺数 Re 的变化情况。在换热器试验

过程中，管内是水蒸气冷凝对流传热，传热系数较大且基本保持不变；管外是空气对流传热，传热系数较小并随着空气流量变化，所以管内的热阻远远小于管外，则管外的对流传热系数近似等于总传热系数。由图可见，两种换热器的总传热系数 K 都随雷诺数 Re 的增大而提高，且螺旋肋片换热器的总传热系数 K 提高得更快。在雷诺数小于 3 000 时，螺旋肋片换热器的总传热系数 K 略小于折流杆换热器，说明在较低的雷诺数下螺旋肋片还不能充分发挥强化传热作用，二者的强化传热作用基本相当；当雷诺数大于3 000 时，螺旋肋片换热器的总传热系数 K 则明显大于折流杆换热器，并且二者的差值呈增大趋势，这说明随着雷诺数增大螺旋肋片的强化传热效果越来越显著，当雷诺数 $Re=6\ 000$ 时螺旋肋片换热器的总传热系数达到 85 W/(m^2·K)，比折流杆换热器高出 13.3%。可见，在试验雷诺数 $Re=3\ 000\sim6\ 500$范围内，螺旋肋片强化壳程传热效果高于折流杆。

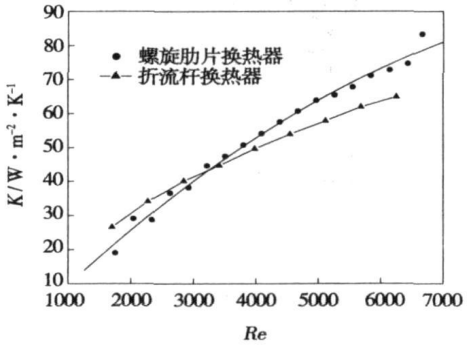


图 4　两种换热器的总传热系数 K 随 Re 的变化

图5 为螺旋肋片换热器和折流杆换热器的压力梯度 ∇P 随雷诺数 Re 的变化。由图可见，两种换热器的压力梯度 ∇P 都随雷诺数 Re 的增大而提高，这是由于流体的粘性和雷诺数增大(即湍流度增大)的缘故。在相同的雷诺数范围内折流杆换热器的压力梯度 ∇P 变化速率更大，证明折流杆对流体的阻挡作用更大，而螺旋肋片对流体几乎无阻挡作用，其阻力增大的原因还是由于流体的粘性和湍流度增大，只不过加装螺旋肋片后比无任何支撑的壳程流体的湍流度增大的速率更快。在雷诺数 2 000～6 500 的范围内，螺旋肋片换热器的压力梯度最大为 80 Pa/m，比折流杆换热器的压力梯度降低了 87.5%，随雷诺数增大二者的压力梯度差值变得更大。可见，在与压降相关的动力消耗方面，螺旋肋片换热器明显低于折流杆换热器。

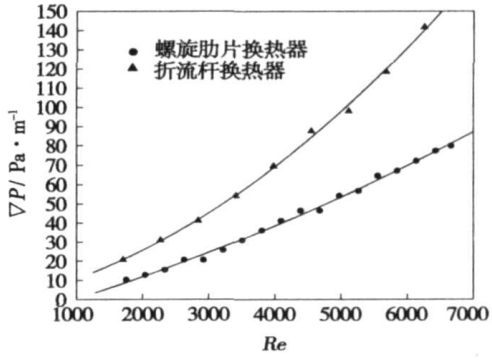
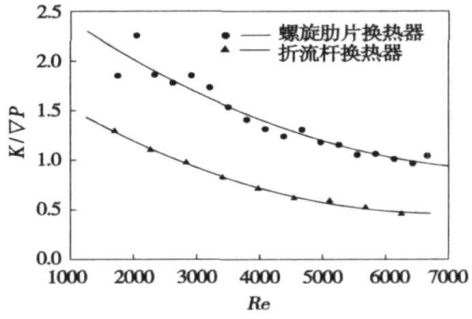


图 5　两种换热器压力梯度 ∇P 的试验值对比

图 6 为相同试验条件下两种换热器的综合性能 $K/\nabla P$ 比较。可见，在试验雷诺数 2 000～6 500 的范围内，螺旋肋片换热器的综合性能 $K/\nabla P$ 明显优于折流杆换热器的综合性能，螺旋肋片换热器的 $K/\nabla P$ 值是折流杆换热器的 1.4～2 倍。



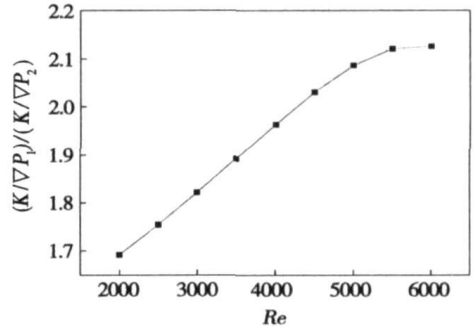


图 6　两种换热器的综合性能 $K/\nabla P$ 对比

4　结　论

(1) 螺旋肋片换热器把制造难度较大的螺旋折流板简化为制造相对容易的围绕单根换热管的螺旋肋片，将流体在壳程总体的螺旋流动变为围绕单根

换热管的局部螺旋流动,并产生大量的涡流和二次流,提高了主流流体和边界层流体的混合程度,可使边界层变薄,从而有效地提高传热系数。相邻换热管间的流体螺旋流动相互作用,可进一步提高流体的湍动程度和强化传热。

(2) 螺旋肋片换热器结构简单,制造和安装方便,节约材料,相对于折流杆换热器有较高的传热系数和较低的压降,试验表明其综合性能 $K/\nabla P$ 明显提高,在试验雷诺数 2 000~6 500 的范围内,螺旋肋片换热器的综合性能 $K/\nabla P$ 值是折流杆换热器的 1.4~2 倍。因此,螺旋肋片换热器具有很好的发展和应用前景。

参考文献:

[1] GENTRY C C. Rodbaffle heat exchanger technology[J]. Chemical Engineering Progress, 1990(7): 48—57.

[2] 吴金星,董其伍,刘敏珊,等. 纵流式换热器的结构研究进展[J]. 化工进展, 2002, 21(5): 306—309.

[3] 严良文,吴金星,王志文. 波形折流杆与弓形折流板换热器的综合性能比较[J]. 压力容器, 2004, 21(4): 10—12.

[4] STRHLIK P. Comparison of correction factors for shell-and-tube heat exchangers with segmental or helical baffles [J]. Heat Transfer Engineering, 1994, 15(1): 55—64.

[5] KRAL D, STEHLIK P, VAN H J, et al. Helical baffles in shell-and tube heat exchangers, Part I: experimental verification [J]. Heat Transfer Engineering, 1996, 17(1): 93—100.

[6] 陈世醒,张克铮,张 强. 螺旋折流板换热器的开发与研究[J]. 抚顺石油学院学报, 1998, 18(3): 31—35.

[7] 王秋旺. 螺旋折流板管壳式换热器壳程传热强化研究进展[J]. 西安交通大学学报, 2004, 38(9): 881—886.

[8] 梅 娜,陈亚平. 螺旋折流片强化壳侧传热研究[J]. 石油化工设备, 2004, 33(5): 1—4

[9] 梅 娜,陈亚平,施明恒. 螺旋折流片换热器壳侧传热与流动的数学模拟[J]. 工程热物理学报, 2005, 26(2): 310—312.

(编辑 滨)

新技术、新工艺

旋汇耦合脱硫技术

目前,在电厂烟气脱硫工艺中,石灰石——石膏脱硫技术因其脱硫效率高、投资较少、运行稳定、副产品可回收利用等优点已成大火电机组脱硫首选。吸收塔是石灰石——石膏脱硫的关键设备,由于石灰石——石膏浆液容易堵塞,许多高效塔如填料塔、板式塔等不能适应。空塔喷淋技术的优点是结构简单、可防堵塞、造价较低、检修量少。缺点是气液接触面小、气体易偏流、塔内停留时间短故脱硫效率低。旋汇耦合技术基于多相紊流掺混的强传质机理,利用气体力学,通过特制的旋汇耦合器能产生气流旋转翻覆湍流空间,使气液固三相充分接触,迅速完成传质过程,从而达到气体净化的目的。旋汇耦合技术与其它石灰石——石膏脱硫技术相比在防堵和维修简便外,因增加了气体旋流速度,提高了脱硫效率和除尘效率。

北京国电清新环保技术工程公司专设有烟气脱硫试验装置,经多年试验研究了旋汇脱硫技术在陡河发电厂实践中,证明该技术的优点有:(1) 烟温下降快,有利于塔内气液充分反应。由于烟温下降快,可不装配 GGH(热交换器),提高了脱硫系统的安全性,降低了投资和维修费;(2) 适应性强。工况和煤种改变时,系统稳定性强,对石灰石粒度要求较宽;(3) 脱硫效率高。从陡河发电厂实践中,平均脱硫效率达 96.79%;(4) 能耗低。由于脱硫效率高,液气比小,溶液循环量小,比同类技术节电能约 8%。

(赵旺初 供稿)

method for the automatic identification of axial trajectory shapes based on improved invariant linear-moment characteristics was put forward, enabling two collected mutually vertical vibration displacement signals to be fitted through a noise treatment into axial trajectories. Improved invariant linear-moments have been adopted to replace a traditional HU's invariable surface moment to calculate the invariant linear-moment eigenvector. With invariant linear-moment eigenvectors of various axial trajectories produced in the simulation process serving as reference modes, the authors have employed correlation to identify the axial trajectory actually tested, and successfully identified the axial trajectory shapes of MJF-30-6 model turbogenerator unit under three different operating conditions. **Key words**: power generator unit, axial trajectory, invariant linear moment, correlation, automatic identification

复杂循环船用燃气轮机间冷器的数值模拟＝**Numerical Simulation of an Intercooler for a Complex-cycle Marine Gas Turbine**[刊, 汉] / LI Zhuo, ZHANG Hui-bing, WEN Xue-you, et al (CSIC No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(2). —148 ~ 152

In an IC (intercooling) cycle gas turbine, intercoolers are components that exercise a major influence on the gas turbine performance. To determine the structural type of the intercoolers to be installed on gas turbines, three intercooler structural schemes have been proposed for a marine gas turbine and a numerical simulation has been performed. Through optimization, relatively good simulation results were obtained. Due to the simplification of a model during the calculation, the pressure-drop loss calculation result is not accurate enough. Consequently, a small flow-passage simulation calculation has been additionally conducted with the pressure-drop loss calculation results in the three schemes being revised. **Key words**: gas turbine, intercooler, intercooling recuperator (ICR) cycle, intercooling (IC) cycle

线性唯象传热规律下复杂系统的热力学优化＝**Thermodynamic Optimization of a Complex System under a Linear Phenomenological Heat Transfer Law**[刊, 汉] / LI Jun, CHEN Lin-gen, SUN Feng-rui (Postgraduate School, Naval University of Engineering, Wuhan, China, Post Code: 430033) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(2). —153 ~ 156

A real heat transfer process does not always follow Newton's heat transfer law and the heat transfer law, however, exercise an enormous influence on the thermodynamic cycle performance. The authors have utilized a commonly used heat transfer law in non-equilibrium thermodynamics, namely, a linear phenomenological heat transfer law, to study a complex system. The latter involves several heat sources at different temperatures, a finite heat capacitance sub-system and a transformer (heat engine or refrigerator). The optimum temperature of the working medium of the transformer and the optimum free temperature of the sub-system have been obtained by using Lagrange Equation. The corresponding maximum power output of the system has also been determined and compared with that calculated by using Newton's heat transfer law. The calculation method under discussion can provide an approach for the calculation of the real temperature distribution and energy limits of a practical complex system. **Key words**: linear phenomenology, heat transfer law, complex system, thermodynamic optimization

螺旋助片自支撑换热器强化换热试验研究＝**An Experimental Study of Intensified Heat Exchange of a Spiral-finned Self-supported Heat Exchanger**[刊, 汉] / WU Jin-xing, ZHU Deng-liang, WEI Xin-li, et al (Energy-saving Technology Research Center, Zhengzhou University, Zhengzhou, China, Post Code: 450001) // Journal of Engineering for Thermal Energy & Power. —2008, 23(2). —157 ~ 160

By utilizing the features of intensified heat transfer of spiral flows to simplify heat exchanger structure and in conjunction with the structural and liquid flow characteristics of spiral-baffle heat exchangers, the authors have developed a spiral-finned self-supported heat exchanger. To have a thorough understanding of the comprehensive performance of the above-cited heat exchanger in respect of heat transfer and pressure drop, a test model and rig have been set up. Under identical test conditions, an experiment to compare the spiral-finned heat exchanger with a baffle rod one has been performed. The results of comparison show that at a Reynolds number of 6000, the total heat transfer coefficient of the spiral-finned heat exchanger will be higher by 13.3% compared with that of a baffle rod one, and the intensified heat transfer effectiveness will become more evident with an increase of the Reynolds number. In the meantime, the pressure gradient will be lowered by 87.5% and the pressure gradient difference between the two types will become bigger with an increase of the Reynolds number. When the Reynolds number is in the range from 2 000 to 6 500, the comprehensive performance $K/\nabla P$ value of a spiral-finned heat exchanger will be 1.4 to 2 times that of the baffle rod one. It can be seen that the spiral-fined heat exchanger enjoys a relatively high heat transfer coefficient and a relatively low pressure drop, and is thus assured of fine development and application prospects. **Key words**: spiral fin, shell-and-tube heat exchanger, self support, baffle rod, intensified heat exchange

加热器上、下端差对机组煤耗影响的通用计算模型＝**A General Calculation Model Featuring the Influence of Upper and Lower Terminal Temperature Difference of a Heater on the Coal Consumption of a Power Plant**[刊, 汉] / YAN Shun-lin, LIU Zhen-gang, XU Hong, et al (Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control, College of Mechanical Engineering, North China Electric Power University, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(2). —161 ~ 164

On the basis of the thermal balance equation, specific inner work equation, cyclic heat absorption equation of a thermal system and the standard coal-consumption calculation formulae of power generation, derived was a general calculation model featuring the influence of lower terminal temperature difference of a heater on the coal consumption of a power plant. Moreover, with the influence of lower terminal temperature difference of a heater being taken into account, the modeling method adopted in the past has been improved. On this basis, a general calculation model of improved type featuring the influence of heater upper terminal temperature difference on the coal consumption of a power plant has also been obtained. Specific case calculations show that both models are characterized by such features as accurate calculation results, ease of use and wide applicability, etc. The models in question can provide a new approach for the analysis of power plant energy-savings and coal consumption reduction, and are thus of major realistic significance. **Key words**: thermal system, heater, upper terminal temperature difference, lower terminal temperature difference, power plant coal consumption

螺纹管中实际冷却水污垢和颗粒污垢的特性研究＝**A Study of Practical Cooling Water- and Particulate Fouling Characteristics in Spiral-grooved Tubes**[刊, 汉] / ZHU Hua, ZHUANG Bo, LI Wei, et al (College of Mechanical and Energy Source Engineering, Zhejiang University, Hangzhou, China, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(2). —165 ~169

An experimental study has been performed of the fouling characteristics of a bare tube and of a group of 7 brass-made in-built spiral-grooved tubes with different thread heights, angles, and different numbers of thread and an inner diameter of 15.54 mm. Through a comparison and analysis of the test data of practical cooling water and particulate fouling, the main reasons for the difference existing between the bare tube and spiral-grooved one have been explained. The authors have