热力工程

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一种基于数据挖掘的入炉燃料发热量在线智能软诊断方法研究

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摘　要: 国内许多火电站燃烧煤质波动对锅炉的稳定燃烧和安全运行构成了严重威胁, 主要矛盾反映在燃料低位发热量太低, 经常在炉内无法稳定燃烧。针对锅炉燃料发热量大范围波动工况下的燃烧数据特性, 提出了关联信息算法和非线性映射网络的混合模型。利用此模型对国内某 300 MW 电站锅炉现场燃烧数据进行了计算和分析, 得到了判断燃料发热量变化的诊断规则知识, 可以较好地预测燃料发热量的变化, 优化运行人员的操作。该方法实施性强, 投入成本小, 而且还可以无缝地集成至现有的 SIS 平台中, 完善锅炉系统的实时性能诊断模块, 提升 SIS 系统二次开发的空间。

关　键　词: 电站锅炉; 数据挖掘; 燃烧优化; 智能诊断; 神经网络; 低位发热量

中图分类号: TK224; TP206　　文献标识码: A

引　言

近年来, 火电站燃料供应周期性紧张, 导致进入锅炉燃烧的煤质特性波动剧烈, 降低了系统的控制品质, 增加了机组运行复杂程度, 严重地影响到锅炉安全经济性运行。许多学者针对此类问题做了大量研究[1~3]。目前国内许多电站锅炉的燃料离线检测的工作程序复杂, 致使这些数据的实时性和完备性差, 难以满足指导运行对象连续调整操作的要求。同时, 在线煤质成份检测装置原理复杂、投资大、维护成本高, 可实施性差, 对于许多老电厂来说更是不实际的。本文提出了一种新的入炉燃料发热量在线软诊断方法, 为锅炉的燃烧调节和优化控制提供了新思路。

1　数据挖掘算法

数据挖掘的过程可粗略地分为: 问题定义、数据准备、数据挖掘以及结果的解释和评估。其中数据准备(数据预处理)和数据挖掘(挖掘算法选择)是整个数据挖掘过程的核心, 它们直接影响到数据挖掘的效率、准确度和最终挖掘模式的有效性。

Apriori 算法是一种最有影响的挖掘布尔关联规则频繁项集的算法[4]。它使用一种称作逐层搜索的迭代方法, 即 δ_k 项集用于探索 $\delta_{(k+1)}$ 项集。首先, 找出频繁 λ_1 项集的集合, 该集合记作 δ_1。δ_1 用于找频繁 λ_2 项集的集合 δ_2, 而 δ_2 用于找 δ_3, 如此下去, 直至找不到频繁 λ_k 项集。找每个 δ_k 需要扫描一次数据库。一旦由数据库 D 中的事务找出频繁项集后, 就可由满足最小支持度和最小置信度的强关联规则公式进行关联分析, 具体算法在此不再赘述。

2　关联规则在燃料发热量诊断和预测中的应用

2.1　可行性分析和研究策略

电厂离线煤质分析的时滞大, 无法满足机组连续运行生产的要求。实际工作中, 操作人员更多的是依靠自己的运行经验, 通过监控炉内燃烧情况和监控仪表提供的锅炉运行状态参数, 及时判断和调整锅炉燃烧, 使其处于最佳的运行状态[5]。

通过适当的方法和技术, 将操作人员的这种有经验的判断和决策过程自动化是完全可行的。依据锅炉不同运行状态、相关运行参数与燃料发热量间的关联信息, 通过数据挖掘技术中的数据统计(data statistics)和自学习(machine learning)的思想来模拟专家知识经验的形成和积累过程, 在线产生预测燃料发热量变化的专家规则知识。同时, 电厂中可靠和完善的数据采集系统(DAS), 也给基于数据挖掘的发热量诊断方法提供了实际操作的可能。

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2.2 数据预处理

数据预处理技术在数据挖掘之前使用，可以提高数据挖掘模式的质量，降低数据挖掘所需要的时间。面对电厂历史数据库中浩瀚的数据，首先要根据特定应用主题，进行数据的清洗和整理。

2.2.1 数据清理

作者到国内某电厂的实际调研，了解到该厂 2005 年 1 月～2005 年 6 月由于受到全国电煤供应紧张的影响，运行中入炉燃烧的煤质很差，发生多次锅炉灭火事故。针对这段时间入厂煤质变化较大的特点，分别提取了一组燃煤入厂时检测的煤粉低位发热量值和机组煤耗值（以天为周期）。两组中的数据样本基本能够覆盖这段期间内煤质发热量和机组煤耗的整个样本空间，具有一定代表性。具体数据如表 1 和表 2 所示。

表 1 某厂 2004 年 11 月～2005 年 1 月入厂检测煤粉低位发热量 (kJ/kg)

	1	2	3	4	5	6	7	8	9
煤粉低位发热量	14756	13642	17097	18517	13863	13844	13785	21522	20418

表 2 某厂 2004 年 11 月～2005 年 1 月机组运行煤耗值 (kg/kWh)

	1	2	3	4	5	6	7	8	9	10	11	12
煤耗值	532	402	417	436	450	548	521	554	485	475	365	409

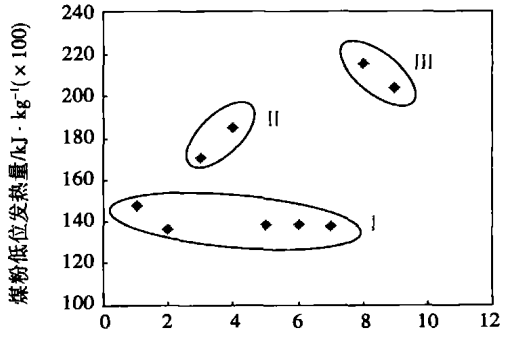

图 1 煤粉低位发热量散点聚类图

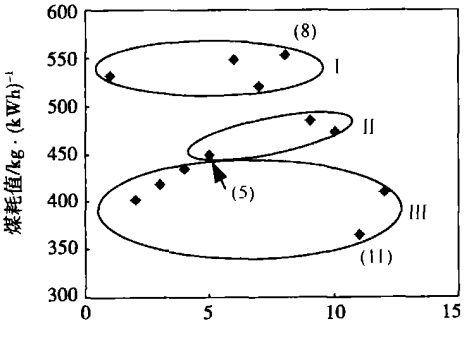

图 2 机组运行煤耗散点聚类图

由于电站实际生产运行特点，上述低位发热量和煤耗值在编号上并不是一一对应，而根据电站煤场传统的作业方式，又无法找出它们之间的对应关系。采用 Kohonen 神经网络对煤粉低位发热量和煤耗值样本进行无导师的聚类学习，可以找到它们的聚类对应关系。其中，神经网络选择了 3×3 的输出层网格，最终保留 3 个输出层结点，产生 3 个聚类，聚类图如图 1 和图 2 所示。根据常理，低位发热量小的聚类对应煤耗值大的聚类，两组中的Ⅰ、Ⅱ、Ⅲ聚类分别对应为低、中、高质煤。为便于分析，提取图 2 中 3 个聚类里的典型值编号 5、8、11 时刻的机组运行参数作为分析数据。

2.2.2 数据集成

综合分析，选取了一组与锅炉燃烧密切相关的 10 个参量数据做为数据挖掘的数据库，它们是汽包压力、主蒸气流量、主蒸气压力、主蒸气温度、炉膛出口烟温、排烟温度、烟气含氧量、总煤量、机组煤耗值和燃料低位发热量[6]。对编号 5、8、11 时刻机组上述运行参数分别采集 1 h（采样周期为 5 s），共 720 组运行数据。最终将 21 600（720×10×3）个数据进行整理和集成，形成挖掘对象数据库。需要特别指出，采集的数据应该是机组在稳定运行工况下的参量数据。

2.2.3 数据变换

由于主蒸汽流量是 3 个不同负荷工况下实时数据，因此不具有可比性，需要构造出新的分析变量。将机组产生的主蒸汽流量与总煤量比值，作为机组的相对主蒸汽流量。然后将相对主蒸汽流量进行最小－最大规范化[4]，构造出相对主蒸汽流量规范数，它表征了单位重量煤粉产生蒸汽量的大小。

2.2.4 数据规约

为了排除现场中一些随机的机组工况波动和运行操作影响，压缩有待分析处理的数据量，对挖掘对象数据库中实时数据采用了线性回归。回归模型为：

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$$Y=\alpha+\beta X \quad (1)$$

其中：α 和β—回归系数。

根据式(1)，每个运行参数分别得到低、中和高质煤工况下的 3 条回归曲线，作为正式数据挖掘应用的预处理后数据。例如，通过数据规约后相对主蒸汽流量规范数的回归曲线为：

$$\begin{cases} y=-0.0004x+0.4107 \ (R^2=5026), \text{低煤质工况} \\ y=-0.0003x+0.277 \ (R^2=0.5057), \text{中煤质工况} \\ y=-0.0006x+0.8484 \ (R^2=0.5653), \text{高煤质工况} \end{cases}$$

其中：R^2—误差平方和。

2.3　燃料发热量关联规则挖掘

采用 Apriori 算法对预处理后的数据进行关联分析。通过反复地调整最小支持度(minsupport)和最小置信度(minconfidence)参数[7]，挖掘对比，确定 minsupport＝0.8，minconfidence＝0.8，attribute significance(属性重要度)＝0.6，最终整理得到 13 条燃料低位发热量的诊断规则。表 3 列出其中 3 条较有价值的规则知识。

表 3　燃料发热量变化在线诊断规则示例

规则编号	前提	结果	支持度/%	置信度/%
1	0.42≤相对主蒸汽流量规范数≤0.85 (或者 125.02≤排烟温度≤125.67)	燃煤低位发热量＞20 000 kJ/kg	100.00	100.00
2	0.06≤相对主蒸汽流量规范数≤0.28 136.71≤排烟温度≤138.80 527.90≤炉膛出口温度≤533.00	15 000 kJ/kg＜燃煤低位发热量＜20 000 kJ/kg	95.00	90.37
3	138.33≤排烟温度≤140.56 536.99≤炉膛出口温度≤541.08	燃煤低位发热量＜15 000 kJ/kg	98.54	96.02

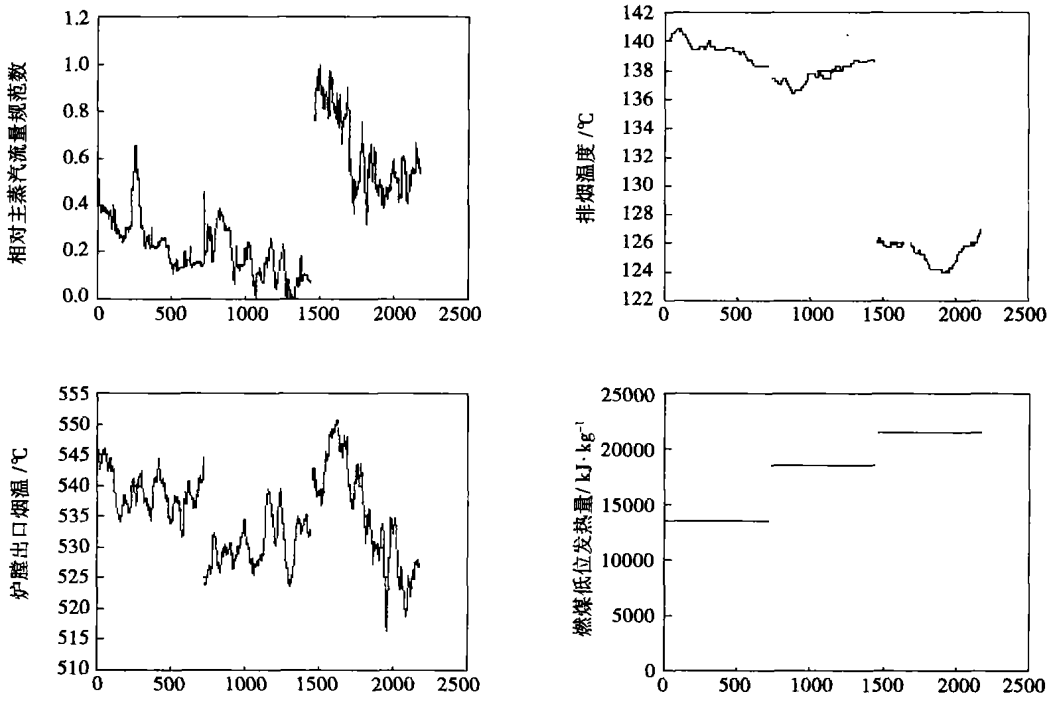

图 3　在 3 个煤质工况下，机组相关运行参数变化曲线

3　发热量关联规则的物理过程分析及判断

通过图 3 显示的实时数据变化曲线，分析上面得到的 3 条规则，可知相对主蒸汽流量规范数是区分高煤质和中低煤质的重要属性。一般来说相对主蒸汽流量规范数越高，燃煤低位发热量越高。在中、低煤质中，通过排烟温度和炉膛出口烟温可将煤质

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发热量进一步划分。这些规则知识也是符合实际的煤粉燃烧物理过程。当煤质燃烧后释放出的热量低时,相对的主蒸汽蒸发量小。同时,低煤质的煤粉往往含有较高的杂质成份,致使其在炉膛中燃烧缓慢,并难以完全燃尽,就被配风带走,造成炉膛出口烟温和排烟温度偏高。高煤质的煤粉在炉内燃烧迅速、发热量大和易燃尽,所以燃烧后产生的蒸汽量大。而且燃烧后的烟气由于充分地与受热面进行了热交换,降低了排烟温度和炉膛出口烟温。

4 结果探讨

(1) 虽然一些有经验的运行操作员或电站专业技术人员也能够得出类似的规则诊断结果,但是通过数据挖掘实现规则知识提取的意义在于:通过数理统计技术和机器学习等人工智能方法,在无需人为干预的情况下,实现了规则知识的自动推理和表达。为今后火电站更高级的人工智能系统(如专家系统 ES、智能决策系统 IDSS)开发奠定了应用基础[8]。

(2) 专家对规则知识的提取是人脑对适量数据推演和归纳的过程,但是面对数据库中海量数据,即使是最简单的规则知识,人脑也很难对其作出判断和提取。对于机器算法,则不存在这样的困惑。事实上,在实际的应用中,可以先用数据挖掘算法对海量数据进行初步的知识挖掘,然后再由领域专家综合更复杂的因素和情况,对机器算法挖掘出的贫乏知识进一步深入挖掘,从而得出较有价值的信息。

(3) 本文中的诊断方法是针对某类具体的应用环境而提出的,应用时应加以区分和注意。如针对主要由燃料低位发热量波动引起的锅炉燃烧问题,采用此方法较为有效。将提取的规则知识以开环的方式显示给操作员,人工地调整和优化燃烧。同时,也可以对规则知识进行适当处理后,以闭环方式引入燃烧控制系统(BMS)中,自动地调节优化锅炉燃烧。

(4) 关于关联规则分析的样本空间,本文只提取了与锅炉燃烧相关的 10 个参数数据集,如果能适当地、合理地引入更多与燃烧有关(间接相关)的参量数据,则可能挖掘出更多深层次的规则知识。

综上所述,利用数据挖掘中的数据智能分析手段,对 300 MW 锅炉燃烧数据进行了关联信息分析,提取了较有价值的煤粉发热量诊断规则知识。结合现场数据曲线,对规则进行了物理过程分析,验证了挖掘结果的正确性,燃烧煤质的规则提取研究,不但为锅炉燃烧煤质实时评估和计量提供了手段,而且为锅炉燃烧优化奠定了理论和实践基础。

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(辉 编辑)

锅炉控制

锅炉机组最佳生态控制系统的构成

据《Энергетика》2006 年 1—3 月号报道,白俄罗斯国立技术大学的专家对锅炉机组最佳生态控制系统进行了探讨和研究。下列措施能够降低锅炉机组的有害排放物:

·改变锅炉炉膛内的过量空气系数; ·烟气再循环;

·把蒸汽或雾化水供入火焰; ·改变热空气的温度。

提出了有关锅炉机组生态控制的数学模型,在使锅炉机组工作经济性降低到最小的同时能使有害排放物(特别是使 NO_x)的排放减少。

根据制定的数学模型提出了生态控制系统,利用微处理机调节器可以实施该系统。

(吉桂明 供稿)

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used separately. In addition, one can also effectively solve such problems as a partial optimization solution and low calculation efficiency, associated with the process of multi-target project searching. The method under discussion can significantly raise the calculation efficiency and efficaciously reduce shafting regulation work load when applied to the parameter analysis of various alignment versions for the shafting of a turbine rotor system, providing a technical safeguard for achieving an ahead-of-schedule reassembly and put-into-operation of steam turbine units. **Key wrods**: turbogenerator unit, rotor alignment parameter, numerical analysis method, optimization of bearing bush adjustment scheme, genetic algorithm

流体静压型指尖密封数值仿真分析＝**A Numerical Simulation Analysis of Hydrostatic Fingertip Seals**[刊, 汉] / WANG Xu (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036), YUE Guo-qiang, ZHANG Wen-ping, ZHENG Qun (College of Power and Nuclear Energy Engineering under the Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy &Power. — 2007, 22(1). —15 ~20

On the basis of analyzing advantages and disadvantages of contact type fingertip seals and hydrodynamic type ones, the authors have presented a hydrostatic fingertip seal and with this type of seal serving as an object of study, established a mathematical model and calculation method for analyzing fluid-solid interaction in the hydrostatic fingertip seals. A numerical calculation and analysis were conducted by taking account of the main factors influencing the leakage and deformation of the above-mentioned seals. The calculation results indicate that the above-mentioned seals enjoy such merits as a small deformation and low leakage. Seal clearance is a main factor influencing the leakage with the circumferential leakage accounting for a major one. The smaller the clearance, the more conspicuous the circumferential leakage. When the pressure difference is constant, the smaller the clearance, the greater the deformation and stress of the hydrostatic pad. When the clearance is constant, the bigger the pressure difference, the greater the deformation and stress of the hydrostatic pad. **Key wrods**: hydrostatic pressure, fingertip seal, fluid-solid coupling, leakage

叶轴形状对旋风子性能影响的研究＝**Research Findings Concerning the Effect of Axle Shapes on the Performance of Cyclone Separators**[刊, 汉] / WANG Zhong-yi, SUN Hai-ou, WANG Song (College of Power and Energy Engineering under the Harbin Engineering University, Harbin, China, Post Code: 150001), WANG Ming-xin (Naval Representative Office Resident in Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy &Power. — 2007, 22(1). —21 ~24

The authors have studied a kind of high-concentration salt-mist separating device-cyclone separator, and numerically simulated under rated operating conditions three models of cyclone separators featuring three axle shapes, namely, 1. hollow cylinder shape, 2. slim solid truncated cone shape and 3. podgy solid circular truncated cone shape. The drag force characteristics of the corresponding models and their separation-efficiency characteristics at different particle diameters have been given. Meanwhile, on a specialized wind tunnel test rig, drag force and separating efficiency characteristics of the three models were also tested. The test results show that model No. 2 has a relatively stable separating efficiency and a comparatively small drag-force loss with its overall performance being better than that of the other two models. When comparing the test results with the numerical simulation ones, one can find that they are in good agreement, thus providing reference data for further investigations. **Key wrods**: salt mist separating device, cyclone separator, axle shape, numerical simulation

一种基于数据挖掘的入炉燃料发热量在线智能软诊断方法研究＝**A Study of the Method for an On-line Intelligent Soft Diagnosis of In-furnace Fuel Low Heating Values Based on Data-mining**[刊, 汉] / LI Bi-cheng (Guangdong Province Yuedian Group Zhuhai Power Station, Zhuhai, China, Post Code: 519050), SHENG Sai-bin (Automation Department, Wuhan University, Wuhan, China, Post Code: 430072) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(1). —25 ~28

Coal quality fluctuations in many Chinese coal-fired power plants have posed a serious threat to boiler stable combustion and safe operation. The main contradiction lies in an excessively low heating value of fuel. Taking account of the charac-

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teristics of combustion data under the conditions of wide-range fluctuations in boiler fuel heating value, the authors have presented a hybrid model composed of a correlation information algorithm and a non-linear mapping network. By making use of the above model, a calculation and analysis has been conducted of the on-site combustion data of a 300 MW utility boiler in China. As a result, obtained was certain diagnostic knowledge governing the change in fuel heating values, which can lead to a better prediction of the change in fuel heating values and an optimized operation by operating personnel. The method can be used conveniently with a low input of outlays. Moreover, it lends itself to be seamlessly integrated into an existing SIS platform to improve the real-time performance diagnostic module of a boiler system and expand the space for the secondary development of a SIS system. **Key wrods**: utility boiler, data mining, combustion optimization, intelligent diagnosis, neutral network, low heating value

基于事例推理技术的锅炉运行实时目标工况模型=**Real-time Target Operating-condition Model for Boiler Operation Based on Instance-and-case Reasoning Techniques**[刊, 汉] / HONG Jun, SI Feng-qi, BI Xiao-long, et al (College of Energy Sources and Environment under the Southeast University, Nanjing, China, Post Code: 210096)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(1). —29 ~ 32

To enhance the operational cost-effectiveness of a power plant, the authors have proposed to adopt a plant synthetic cost-based coal consumption to serve as a comprehensive evaluation criterion for boiler operation. Meanwhile, a definition was given for the target operating-condition of a boiler. By making a steady-state judgement of the original operating condition database of a boiler non-steady-state operating conditions have been filtered out. On this basis through a similitude calculation, the steady-state operating conditions of the boiler can be classified into different groups of operating conditions to obtain the optimal ones in various operating condition groups by assuming the synthetic cost-based coal consumption of the boiler unit as a judgement criterion. With the establishment of a boiler-operation target operating condition database, which serves as a case-and-instance database, retrieved was the target operating condition corresponding to the current practical one by using the instance and case-based reasoning techniques. Practical applications show that the model can automatically track the changes in boiler operation characteristics. The accuracy and efficiency in retrieving the target operating condition can meet the real-time requirements for operation optimization, providing an important means for operation optimization of utility boilers. **Key wrods**: boiler, target operating condition, instance and case-based reasoning, fuzzy matching

基于雨流计数法的锅炉汽包寿命实时监测=**Boiler Drum Life Real-time Monitoring Based on a Rain-flow Counting Method**[刊, 汉] / WANG Zhang-qi, JIANG Wen-qiang, AN Li-qiang (College of Mechanical Engineering under the North China University of Electric Power, Baoding, China, Post Code: 071003)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(1). —33 ~ 37

A model for monitoring the temperature and stress profiles of boiler drums has been established. Based on the start-up data of a boiler drum acquired from the DCS (distributed control system) of a power plant, the hazardous point on the boiler drum can be determined from a finite element analysis and the stress concentration factor at that point also corrected. An implicit difference method to calculate the transient temperature profile of the boiler drum and the equivalent stress calculation formula of the hazardous point were given, thereby improving the rain-flow counting method. Proposed is a criterion for judging the completion of boiler drum startup and shutdown process by adopting a stress stabilization principle. The number of different stress amplitude cycles at each startup and shutdown process was added up and on this basis the life wastage of the boiler drum determined. By analyzing the data acquired from a cold startup of the boiler drum, the authors have verified the effectiveness of the method under discussion and thereby developed a real-time system for monitoring the service life of boiler drums. The boiler drum monitoring operation of a 600 MW turbo-generator boiler drum shows the effectiveness of the method in achieving the aim of performing a real-time monitoring of boiler drum life wastage and of providing guidance for their operation. **Key wrods**: boiler drum, fatigue life, rain-flow counting method, cold-state startup, real-time monitoring

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