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核电站蒸汽发生器再循环水质量流量实时估计方法

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摘要: 根据蒸汽发生器的实际结构,将蒸汽发生器划分为热段、冷段、汽水分离器和汽室,热段和冷段又划分为下降通道和上升通道.基于质量、能量、动量守恒定律,依次建立蒸汽发生器热段、冷段、汽水分离器和汽室分布的参数模型.结合工质物性参数数据库和数据采集系统(DCS)实时测量数据实时求解模型,从而获得蒸汽发生器再循环水的质量流量估计值.采用某CPR1000核电机组运行数据的验证结果表明,由所提方法解算得到的蒸汽发生器顶部出口饱和蒸汽温度、压力和流量与实测值吻合较好,从而间接证实了蒸汽发生器再循环水质量流量估计的正确性.

关键词: 蒸汽发生器;分布参数模型;再循环水;质量流量;实时估计

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A Real-Time Mass Flow Rate Estimation Method of Recirculation Water in Steam Generator of Nuclear Power Plants

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Abstract: According to its actual structure, the steam generator is divided into the hot leg, the cold leg, the steam-water separator, and the steam chamber, where the hot leg and the cold leg are further divided into a descending channel and an ascending channel. Based on the mass, energy, and momentum conservation laws, the distribution parameter models for the hot leg, the cold leg, the steam-water separator, and the steam chamber are established. Combining the physical parameter database of the working medium and the data collection system (DCS) real-time measurement data, the model is solved in real time and the estimated mass flow rate of recirculation water is obtained. The verification results using the operating data of a CPR1000 nuclear power unit show that the calculated temperature, the pressure, and the mass flow rate of the outlet saturated steam of the steam generator agree well with the measured values, which indirectly verifies the correctness of the estimation approach of recirculation water proposed in this paper.

Key words: steam generator; distributed parameter model; recirculation water; mass flow rate; real-time estimation

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段下降通道液相工质密度; A_{H_D} 为热段下降通道的横截面积; H 为下降通道的水位高度; $g_{m, fw}$ 为给水质量流量; $g_{m, rw}$ 为再循环水质量流量; g_{m, H_D_o} 为热段下降通道出口液相工质质量流量; c_{H_D} 为热段下降通道液相工质的定压比热容; T_{H_D} 为热段下降通道液相工质温度; h_{fw} 为给水比焓; h_{rw} 为再循环水比焓; h_{H_D} 为热段下降通道液相工质比焓; $h_{H_D_o}$ 为热段下降通道出口液相工质比焓; p_{H_D} 为热段下降通道液相工质压力; g_{m, H_D} 为热段下降通道液相工质质量流量; f_{H_D} 为热段下降通道摩擦因子; D_{H_D} 为热段下降通道当量直径; g 为重力加速度。

考虑热段上升通道二回路工质重力压降、摩擦压降和加速压降, 根据动量、质量和能量守恒原理, 所得热段上升通道模型为

$$\frac{\partial \rho_{H_R}}{\partial t} + \frac{\partial \rho_{H_R} v_{H_R}}{\partial z} = 0 \quad (5)$$

$$\frac{\partial \rho_{H_M} c_{H_M} T_{H_M}}{\partial t} = n K_{H_R_P} \pi d_{H_M} (T_{H_R_P} - T_{H_M}) \quad (6)$$

$$\frac{\partial \rho_{H_R_P} c_{H_R_P} T_{H_R_P}}{\partial t} + \frac{\partial \rho_{H_R_P} c_{H_R_P} T_{H_R_P} v_{H_R_P}}{\partial z} = n K_{H_R_P} \pi d_{H_M} (T_{H_M} - T_{H_R_P}) \quad (7)$$

$$\frac{\partial \rho_{H_M} c_{H_M} T_{H_M}}{\partial t} = n K_{H_R_B} \pi d_{H_M} (T_{H_R_B} - T_{H_M}) \quad (8)$$

$$\frac{\partial \rho_{H_R_B} c_{H_R_B} T_{H_R_B}}{\partial t} + \frac{\partial \rho_{H_R_B} c_{H_R_B} T_{H_R_B} v_{H_R_B}}{\partial z} = n K_{H_R_B} \pi d_{H_M} (T_{H_M} - T_{H_R_B}) \quad (9)$$

$$-\frac{\partial p_{H_R_P}}{\partial z} = \frac{\partial g_{m, H_R_P}}{\partial t} + \frac{\partial}{\partial z} \left(\frac{g_{m, H_R_P}^2}{\rho_{H_R_P}} \right) + \frac{f_{H_R_P} g_{m, H_R_P}^2}{2 \rho_{H_R_P} D_{H_R_P}} \phi^2 + \rho_{H_R_P} g + \xi_{H_R_P} \frac{g_{m, H_R_P}^2}{\rho_{H_R_P}} \quad (10)$$

$$-\frac{\partial p_{H_R_B}}{\partial z} = \frac{\partial g_{m, H_R_B}}{\partial t} + \frac{\partial}{\partial z} \left(\frac{g_{m, H_R_B}^2}{\rho_{H_R_B}} \right) + \frac{f_{H_R_B} g_{m, H_R_B}^2}{2 \rho_{H_R_B} D_{H_R_B}} \phi^2 + \rho_{H_R_B} g + \xi_{H_R_B} \frac{g_{m, H_R_B}^2}{\rho_{H_R_B}} \quad (11)$$

$$\phi^2 = \left[1 + x \left(\frac{\rho_w}{\rho_s} - 1 \right) \right] \left[1 + x \left(\frac{\mu_w}{\mu_s} - 1 \right) \right] \quad (12)$$

式中: ρ_{H_M} 为热段倒 U 型管金属壁密度; ρ_{H_R} 为热段上升通道工质密度; $\rho_{H_R_P}$ 为热段上升通道预热区液相工质密度; $\rho_{H_R_B}$ 为热段上升通道沸腾区气液混合相工质密度; v_{H_R} 为热段上升通道工质的流速; $v_{H_R_P}$ 为热段上升通道预热区液相工质的流速; $v_{H_R_B}$ 为热段上升通道沸腾区气液混合相工质的流速; c_{H_M} 为热段倒 U 型管金属壁的定压比热容; $c_{H_R_P}$ 为热段上升通道预热区液相工质的定压比热容; $c_{H_R_B}$ 为热段上升通道沸腾区气液混合相工质的定压比热容; $D_{H_R_P}$ 为热段上升通道预热区水力直

径; $D_{H_R_B}$ 为热段上升通道沸腾区水力直径; T_{H_M} 为热段倒 U 型管金属壁温度; $T_{H_R_P}$ 为热段上升通道预热区液相工质温度; $T_{H_R_B}$ 为热段上升通道沸腾区气液混合相工质温度; n 为倒 U 型管数目; $p_{H_R_P}$ 为热段上升通道预热区液相工质压力; $p_{H_R_B}$ 为热段上升通道沸腾区气液混合相工质压力; g_{m, H_R_P} 为热段上升通道预热区液相工质的质量流量; g_{m, H_R_B} 为热段上升通道沸腾区气液混合相工质的质量流量; $f_{H_R_P}$ 为热段上升通道预热区摩擦因数; $f_{H_R_B}$ 为热段上升通道沸腾区摩擦因数; $\xi_{H_R_P}$ 为热段上升通道预热区局部阻力系数; $\xi_{H_R_B}$ 为热段上升通道沸腾区的局部阻力系数; d_{H_M} 为热段倒 U 型管内径; ϕ 为两相倍乘因子; x 为质量气含率; ρ_w 为上升通道液相工质密度; ρ_s 为上升通道饱和蒸汽密度; μ_w 为上升通道液相工质黏性系数; μ_s 为上升通道饱和蒸汽黏性系数; $K_{H_R_P}$ 为热段上升通道预热区二回路工质与倒 U 型管金属壁间的传热系数; $K_{H_R_B}$ 为热段上升通道沸腾区二回路工质与倒 U 型管金属壁间的传热系数。

考虑热段一回路冷却剂重力压降, 根据动量、质量和能量守恒原理, 可得热段一回路模型为

$$\frac{\partial \rho_{H_P}}{\partial t} + \frac{\partial \rho_{H_P} v_{H_P}}{\partial z} = 0 \quad (13)$$

$$\frac{\partial \rho_{H_P} c_{H_P} T_{H_P}}{\partial t} + \frac{\partial \rho_{H_P} c_{H_P} T_{H_P} v_{H_P}}{\partial z} = K_{H_P} \pi d_{H_M} (T_{H_M} - T_{H_P}) \quad (14)$$

$$\frac{\partial \rho_{H_M} c_{H_M} T_{H_M}}{\partial t} = K_{H_P} \pi d_{H_M} (T_{H_P} - T_{H_M}) \quad (15)$$

$$\frac{\partial p_{H_P}}{\partial z} = -\rho_{H_P} g \quad (16)$$

式中: ρ_{H_P} 为热段一回路冷却剂的密度; v_{H_P} 为热段一回路冷却剂的流速; c_{H_P} 为热段一回路冷却剂的定压比热容; T_{H_P} 为热段一回路冷却剂的温度; p_{H_P} 为热段一回路冷却剂的压力; K_{H_P} 为热段一回路冷却剂通过倒 U 型管金属壁向二回路工质传热的传热系数。

一回路冷却剂向预热区二回路工质的传热为管内强制对流换热, 采用 Dittus-Boelter 公式计算传热系数^[16-17], 则有:

$$K_{PR} = 0.023 Re_w^{0.8} Pr_w^{0.3} \lambda_w / d_{H_M} \quad (17)$$

式中: K_{PR} 为预热区一回路冷却剂通过倒 U 型管金属壁向预热区二回路工质传热的传热系数; Re_w 为一回路冷却剂雷诺数; Pr_w 为一回路冷却剂普朗特数; λ_w 为一回路冷却剂热导率。

对二回路沸腾区采用 Chen 公式计算传热系数^[18-19], 则有:

$$K_{BR} = K_{cht} + K_{bht} \tag{18}$$

$$K_{cht} = 0.023 \left[\frac{g_m(1-x)d_{H_M}}{\mu_w} \right]^{0.8} Pr_w^{0.4} \frac{\lambda_w}{d_{H_M}} F \tag{19}$$

$$F = \begin{cases} 1.0, & \frac{1}{X_{tt}} \leq 0.1 \\ 2.35 \left(\frac{1}{X_{tt}} + 0.213 \right)^{0.736}, & \frac{1}{X_{tt}} > 0.1 \end{cases} \tag{20}$$

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\rho_s}{\rho_w} \right)^{0.5} \left(\frac{\mu_s}{\mu_w} \right)^{0.1} \tag{21}$$

$$K_{bht} = 0.00122 \frac{\rho_w^{0.49} c_w^{0.45} \lambda_w^{0.79}}{\rho_s^{0.24} h_{fs} \sigma^{0.49} \mu_w^{0.29}} \Delta T_{MT}^{0.24} \Delta p_{MT}^{0.75} S \tag{22}$$

$$S = \begin{cases} \frac{1}{1 + 3.305 \times 10^{-6} Re_w^{1.14}}, & Re_w \leq 3.25 \\ \frac{1}{1 + 0.42 Re_w^{0.78}}, & 32.5 < Re_w < 70 \\ \frac{1}{10}, & Re_w > 70 \end{cases} \tag{23}$$

式中： K_{BR} 、 K_{cht} 、 K_{bht} 分别为沸腾区、沸腾区对流传热部分和沸腾区泡核沸腾传热部分的传热系数； g_m 为质量流量； σ 为沸腾区液相工质表面张力系数； c_w 为一回路冷却剂定压比热容； h_{fs} 为沸腾区液相工质的汽化潜热； ΔT_{MT} 为沸腾区倒 U 型管金属壁过热度； Δp_{MT} 为沸腾区饱和蒸汽压差。

汽水分离器稳态模型为

$$g_{m,ss,S_o} = \eta(x_{H_{R_{B_o}}} g_{m,H_{R_{B_o}}} + x_{C_{R_{B_o}}} g_{m,C_{R_{B_o}}}) \tag{24}$$

$$g_{m,sw,S_o} = (1 - \eta x_{H_{R_{B_o}}}) g_{m,H_{R_{B_o}}} + (1 - \eta x_{C_{R_{B_o}}}) g_{m,C_{R_{B_o}}} \tag{25}$$

$$p_{S_o} = p_{S_i} - \xi_{SP} \frac{g_{m,S_i}^2}{\rho_{S_i}} \tag{26}$$

$$g_{m,S_i} = g_{m,H_{R_{B_o}}} + g_{m,C_{R_{B_o}}} \tag{27}$$

$$p_{S_i} = p_{H_{R_{B_o}}} = p_{C_{R_{B_o}}} \tag{28}$$

$$\rho_{S_i} = \rho_{H_{R_{B_o}}} = \rho_{C_{R_{B_o}}} \tag{29}$$

式中： $g_{m,H_{R_{B_o}}}$ 为热段上升通道沸腾区出口气液混合相工质的质量流量； $g_{m,C_{R_{B_o}}}$ 为冷段上升通道沸腾区出口气液混合相工质的质量流量； g_{m,ss,S_o} 为汽水分离器出口饱和蒸汽的质量流量； g_{m,sw,S_o} 为汽水分离器出口饱和水的质量流量； g_{m,S_i} 为汽水分离器入口气液混合相工质质量流量； $x_{H_{R_{B_o}}}$ 为热段上升通道沸腾区出口气液混合相工质的质量气含率； $x_{C_{R_{B_o}}}$ 为冷段上升通道沸腾区出口气液混合相工质的质量气含率； η 为汽水分离器效率； $p_{H_{R_{B_o}}}$ 为热段上升通道沸腾区出口气液混合相工质压力； $p_{C_{R_{B_o}}}$ 为冷段上升通道沸腾区出口气液混合相工质压力； p_{S_i} 为汽水分离器入口气液混合相工质压力；

p_{S_o} 为汽水分离器出口饱和蒸汽压力； $\rho_{H_{R_{B_o}}}$ 为热段上升通道沸腾区出口气液混合相工质密度； $\rho_{C_{R_{B_o}}}$ 为冷段上升通道沸腾区出口气液混合相工质密度； ξ_{SP} 为汽水分离器局部阻力系数； ρ_{S_i} 为汽水分离器入口气液混合相工质密度。

汽室动态模型为

$$\tau \frac{dg_{m,SC_o}}{dt} = g_{m,SC_i} - g_{m,SC_o} \tag{30}$$

式中： g_{m,SC_i} 为汽室入口饱和蒸汽质量流量； g_{m,SC_o} 为汽室出口饱和蒸汽质量流量； τ 为时间常数。

2 模型验证

模型验证数据来自某 1 000 MW 核电机组。该核电机组蒸汽发生器设计参数如表 1 所示。分布式控制系统实时数据采样时间间隔 $\Delta t=5$ s。数据包括机组负荷、给水温度、给水压力、给水质量流量、饱和蒸汽温度、饱和蒸汽压力、饱和蒸汽质量流量、一回路冷却剂进出口温度、一回路冷却剂进出口压力、一回路冷却剂进出口质量流量以及一回路冷却剂进出口水位高度等。由于给水压力和一回路冷却剂压力及质量流量在核电站变负荷过程中变化较小，所以取其测量均值。给水压力取为 6.7 MPa，一回路冷却剂压力取为 15.4 MPa，一回路冷却剂体积流量取为 23 790 m³/h。基于工质物性参数数据库和蒸汽发生器结构参数库，采用 Runge-Kutta 法解算热段模型、冷段模型、汽水分离器模型和汽室模型，输出蒸汽发生器再循环水质量流量估计值。输出的结果作为下降通道模型的输入，进行下一步解算。

表 1 某 1 000 MW 核电机组蒸汽发生器设计参数

Tab.1 Rated parameters of steam generator in a 1 000 MW nuclear power unit

参数	取值
机组额定功率/MW	1 000
倒 U 型管数目	4 474
倒 U 型管计算高度/m	9.36
倒 U 型管平均直径/mm	17.96
倒 U 型管厚度/mm	1.09
$w_1/\%$	80
$w_2/\%$	50

核电机组于 2019 年 5 月 10 日 15:00—16:00 的输出功率变化曲线及水位高度实测值如图 2 所示，其中： P 为机组输出功率，其间由 1 030 MW 下降到 690 MW。蒸汽发生器实测给水温度、一回路冷

却剂进出口温度如图 3 所示,其中: T 为温度. 在该时段出口饱和蒸汽质量流量、压力和温度的模型仿真值与实测值对比如图 4 和 5 所示. 其中: T_{sc_o} 为汽室出口饱和蒸汽温度; p_{sc_o} 为汽室出口饱和蒸汽压力. 由图 4 和 5 可知,蒸汽发生器出口饱和蒸汽的温度、压力和质量流量最大相对误差分别为 1.41%, 0.17% 和 1.72%, 从工程上看这些误差已经很小, 从而验证了所建立模型的准确性. 给水质量流量实测值和再循环水质量流量的实时估计值如图 6 所示. 由图 6 可知,再循环水流量随着核电机组负荷的降低逐渐下降.

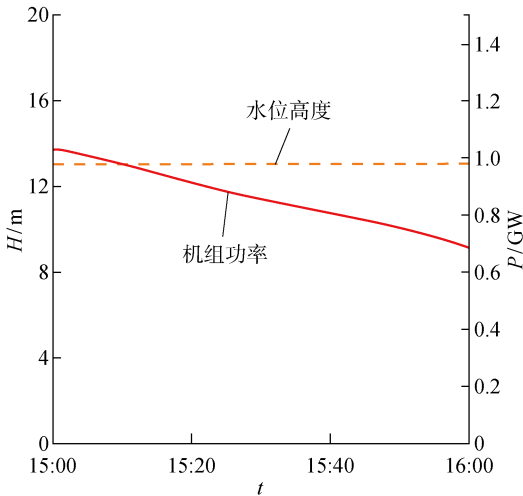


图 2 某 1 000 MW 核电机组输出功率及蒸汽发生器水位高度实测值

Fig. 2 Output power of a 1 000 MW nuclear power unit and measured water level of steam generator

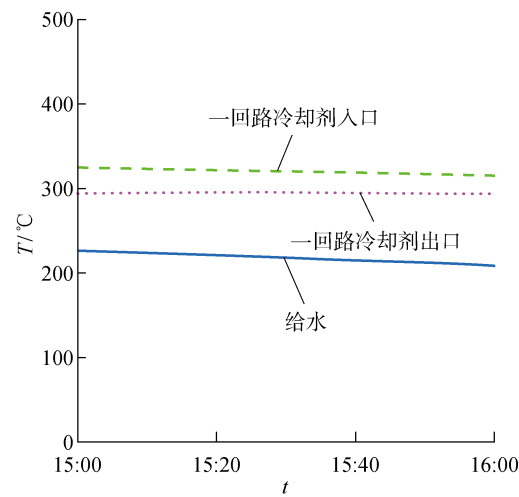


图 3 蒸汽发生器工质温度测点

Fig. 3 Measured temperatures of working mediums in steam generator

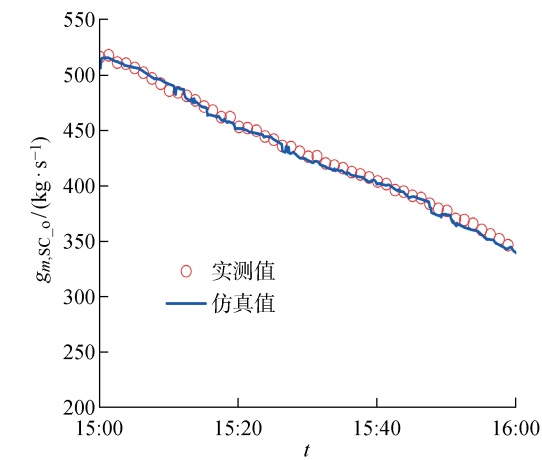


图 4 蒸汽发生器出口饱和蒸汽质量流量

Fig. 4 Mass flow rate of saturated steam at outlet of steam generator

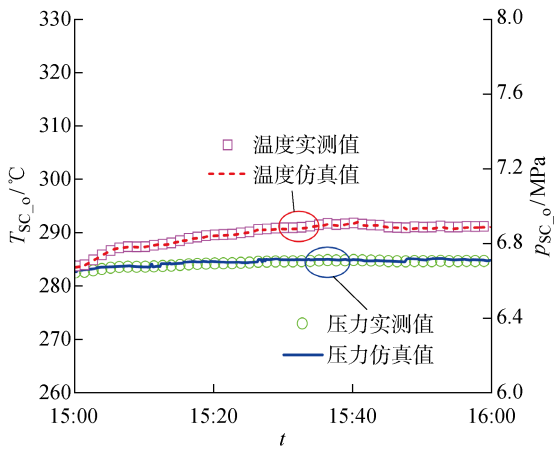


图 5 蒸汽发生器出口饱和蒸汽压力和温度

Fig. 5 Pressure and temperature of saturated steam at outlet of steam generator

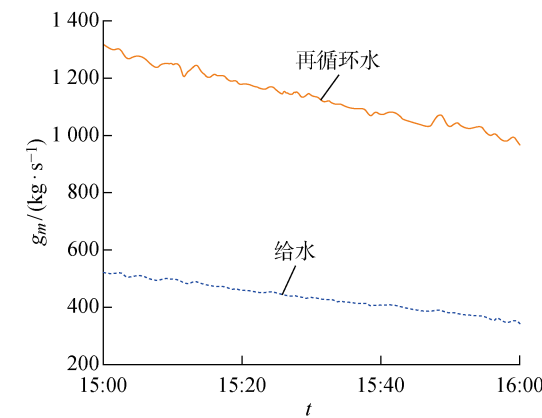


图 6 蒸汽发生器给水质量流量实测值和再循环水质量流量估计值

Fig. 6 Measured mass flow rate of feedwater and estimated mass flow rate of recirculation water of steam generator

由式(1)~(30)构成的蒸汽发生器分布参数系统是机理模型,比较复杂,但对如图2所示的3600 s时间区间和5 s仿真步长,采用i7 PC机(4CPU,主频3.4 GHz)所需的仿真时间是994 s,即每步仿真消耗的计算时间为1.38 s,故所提模型的应用具有实时性保障。

3 结语

本文对蒸汽发生器再循环水质量流量估计问题进行了研究。首先,根据蒸汽发生器的实际几何结构对其进行结构简化,将其划分为热段、冷段、汽水分离器和汽室4部分。然后,基于质量、动量和能量守恒定律,建立所划分的热段、冷段、汽水分离器和汽室分布参数模型。最后,结合工质物性参数数据库和某核电机组分布式控制系统的实时测量数据进行模型解算。基于模型仿真得到的蒸汽发生器出口饱和蒸汽温度、压力和质量流量的计算值与实测值吻合得较好,从而验证了本文所建立模型的准确性,也间接说明了作为实时仿真输出变量之一的再循环水质量流量实时估计的准确性。

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