[0008] At this point, rather than sending the filtration element to a laboratory, the operator may try to rely on experience to guess the type of fouling/scaling occurring and clean the system using chemicals they believe may be appropriate. In such instances, the type of chemicals used may not be appropriate and may not address the actual fouling/scaling occurring. This can result in a cleaned filtration element having a performance baseline lower than the performance level the filtration element would have if proper cleaning was performed. After repeated cleaning attempts, the filtration elements and/or the water treatment facility can encounter additional operational breakdowns, resulting in increased costs in operation and inadequately filtered water.

SUMMARY

[0009] The exemplary system for determining filter status can be used by plant operators to improve their system performance. The system can analyze past performance to identify past cleaning-in-place (CIP) events and the type of filtration module failure modes based on the performance of the system in the inter and intra-CIP periods. The system can be used for nanofiltration and/or reverse osmosis systems to identify fouling, scaling, and/or membrane failure modes. In some embodiments, the system can be used to predict when the next cleaning should/will take place and to recommend the most suitable cleaning procedure.

[0010] Membrane fouling is a complicated issue in nanofiltration and reverse osmosis systems. As such, identifying the dominant fouling mechanism during the filtration process can be of great significance for the prediction of the next cleaning cycle and for control of fouling. The real-time (or substantially real-time) monitoring of the water treatment facility to detect and identify fouling types allows for early detection and reaction of the facility operators to prevent excessive fouling and potentially negative effects on the rest of the system. The system provides an accurate means for determining the type of fouling occurring, and thereby provides accurate recommendations for the cleaning cycle to ensure steps are taken to properly address the fouling event(s). In some embodiments, the system can be used to anticipate cyclical and/or seasonal fouling, such that fouling event(s) can be minimized and/or avoided.

[0010a] In an aspect, the present disclosure refers to a system for determining a filter status, comprising:

a database configured to electronically store data, the data including past performance data of one or more water filtration elements; and

a processing device in communication with the database, the processing device is configured to:

receive as input the past performance data;

identify one or more data points within the past performance data indicative of a cleaning event for the one or more water filtration elements;

divide the past performance data into individual data segments, each of the individual data segments representing data of the past performance data in-between respective identified cleaning events;

fit a mathematical function to each of the individual data segments; and

identify a type of fouling occurring during each of the individual data segments based on the mathematical function fitted to the respective individual data segment.

[0010b] In an aspect, the present disclosure refers to a method for determining a filter status, comprising:

receiving as input to a system for determining a filter status past performance data of one or more water filtration elements, the system for determining the filter status including (i) a database configured to electronically store the past performance data, and (ii) a processing device in communication with the database;

identifying one or more data points within the past performance data indicative of a cleaning event for the one or more water filtration elements;

dividing the past performance data into individual data segments, each of the individual data segments representing data of the past performance data in-between respective identified cleaning events;

fitting a mathematical function to each of the individual data segments; and

identifying a type of fouling occurring during each of the individual data segments based on the mathematical function fitted to the respective individual data segment.

[0010c] In an aspect, the present disclosure refers to a non-transitory computer-readable medium storing instructions for determining a filter status that are executable by a processing device, wherein execution of the instructions by the processing device causes the processing device to:

receive as input to a system for determining a filter status past performance data of one or more water filtration elements, the system for determining the filter status including (i) a database configured to electronically store the past performance data, and (ii) the processing device in communication with the database;

identify one or more data points within the past performance data indicative of a cleaning event for the one or more water filtration elements;

divide the past performance data into individual data segments, each of the individual data segments representing data of the past performance data in-between respective identified cleaning events;

fit a mathematical function to each of the individual data segments; and

identify a type of fouling occurring during each of the individual data segments based on the mathematical function fitted to the respective individual data segment.

[0011] In accordance with examples of the present disclosure, an exemplary method for analyzing the performance of a feedwater filtration system is provided. The method includes collecting performance data from said filtration system, normalizing said dataset to

generate said differencing series for dP and Pf, calculating the average and standard deviations of said differencing series for dP and Pf, comparing each value in the differencing series for dP or Pf to the sum of the corresponding differencing series and the product of a Differencing Constant and the corresponding standard deviation of the differencing series, checking if there is a gap in the dataset, and checking if the gap is wider than a CIP Reference Time. The Differencing Constant is a positive whole number, preferably a number from 1 to 10, inclusive; more preferably a number from 3 to 7, inclusive; and still more preferably 5. The CIP Reference time is a time interval defined by the user as indicative of a typical duration of a CIP for the system of interest and can range from minutes to days. An exemplary value for the CIP Reference time can be, e.g., 120 minutes, 1 day, or the like. Preferred CIP Reference times are from 5 minutes to two weeks, and 1 day is a more preferred CIP Reference time.

[0015] In determining the type of fouling occurring in the filtration element(s), the system analyzes data from the filtration element(s) to determine whether a variety of parameters are met. As discussed herein, some parameters are considered "primary" parameters and some parameters are considered "secondary" (e.g., optional) parameters depending on the fouling type involved. For each fouling type, there may be one or more primary parameters and one or more secondary parameters. In some instances, the data can meet the criteria for, e.g., only one primary parameter, more than one primary parameter, only one or more secondary parameters, or the like. The system can therefore initially review the data to determine whether one or more of the primary parameters are met. If so, the system can estimate the fouling type based on the primary parameter(s) met. In some examples, the system can estimate the fouling type based on only one primary parameter that has been met. In some examples, the system can rely on additional primary parameters and/or secondary parameters that have been met to solidify, reinforce or support the original estimate of the fouling type occurring based on the original primary parameter that has been met. The system can therefore initially determine if a primary parameter has been met to estimate the fouling type. If no primary parameters have been met, the system can review the secondary parameters to estimate the fouling type based on the secondary parameter(s) that have been met. In some examples, if overlap exists between the possible fouling types based on the primary and/or secondary parameter(s) met, the system can perform a ranking operation to determine the likelihood of the type of fouling type occurring, e.g., based on historical data, or the like. Although some

parameters are discussed as being based on 1st or 2nd order polynomial functions, in some examples, the parameters can be identified based on, e.g., exponential functions, higher order polynomial functions, linear functions, non-linear functions, or the like.

[0016] Fitting of a set of curves to said data segments can be performed using a statistical means. In some examples, the mode of filtration module failure in a data segment can be identified as scaling if at least one of the following conditions is met: (a) the coefficient of determination of dP to a 1st order polynomial is greater than 0.7, (b) the coefficient of determination of dP to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to dP is less than 0.3, (d) the coefficient of determination of Sp to a 1st order polynomial is greater than 0.7, (e) the coefficient of determination of Sp to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to Sp is less than 0.3, (g) the coefficient of determination of Pf to a 1st order polynomial is greater than 0.7, (h) the coefficient of determination of Pf to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to Pf is less than 0.3, (j) dP increases with time in said data segment, (k) Pf decreases with time in said data segment, and/or (l) Sp increases with time in said data segment.

[0017] In some examples, the mode of filtration module failure in a data segment can be identified as particulate fouling if at least one of the following conditions is met: (a) the coefficient of determination of dP to a 1st order polynomial is greater than 0.7, (b) the coefficient of determination of dP to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to dP is less than 0.3, (d) the coefficient of determination of Pf to a 1st order polynomial is greater than 0.7, (e) the coefficient of determination of Pf to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to Pf is less than 0.3, (g) the coefficient of determination of Sp to a 1st order polynomial is greater than 0.7, (h) the coefficient of determination of Sp to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to Sp is less

than 0.3, (j) dP increases over time in said data segment, (k) Pf decreases over time in said data segment, and/or (l) Sp increases with time in said data segment.

[0018] In some examples, the mode of filtration module failure in a data segment can be identified as biofouling if at least one of the following conditions is met: (a) the coefficient of determination of dP to a 1st order polynomial is greater than 0.4, (b) the coefficient of determination of dP to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination values for 2nd order and 1st order polynomials is greater than 0.3, (d) the coefficient of determination of Pf to a 1st order polynomial is greater than 0.4, (e) the coefficient of determination of Pf to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to Pf is greater than 0.3, (g) the coefficient of determination of Sp to a 1st order polynomial is greater than 0.4, (h) the coefficient of determination of Sp to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to Sp is greater than 0.3, (j) dP increases over time in said data segment, (k) Pf decreases over time in said data segment, and/or (l) Sp increases over time in said data segment.

[0019] In some examples, the mode of filtration module failure in a data segment can be identified as membrane integrity failure (e.g., due to oxidation or membrane damage, or the like) if at least one of the following conditions is met: (a) the coefficient of determination of Pf to a 1st order polynomial is greater than 0.7, (b) the coefficient of determination of Pf to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination values for the 2nd order and 1st order polynomials fitted to Pf is less than 0.3, (d) the coefficient of determination of Sp to a 1st order polynomial is greater than 0.7, (e) the coefficient of determination of Sp to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to fitted to Sp is less than 0.3, (g) the coefficient of determination of dP to a 1st order polynomial is greater than 0.7, (h) the coefficient of determination of dP to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to dP is less than 0.3, (j) dP remains constant with time in said data segment, (k) Pf increases over time in said data segment, and/or (l) Sp increases over time in said data segment.

[0020] In some examples, the mode of filtration module failure in a data segment can be identified as organic fouling if at least one of the following conditions is met: (a) the coefficient of determination of Pf to a 1st order polynomial is greater than 0.4, (b) the coefficient of determination of Pf to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination values for the 2nd order and 1st order polynomials fitted to Pf is greater than 0.3, (d) the coefficient of determination of Sp to a 1st order polynomial is greater than 0.4, (e) the coefficient of determination of Sp to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to fitted to Sp is greater than 0.3, (g) the coefficient of determination of dP to a 1st order polynomial is greater than 0.7, (h) the coefficient of determination of dP to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination values for 2nd order and 1st order polynomials fitted to dP is less than 0.3, (j) dP remains constant with time in said data segment, (k) Pf decreases over time in said data segment, and/or (l) Sp decreases over time.

[0021] In some examples, said drop limit can be greater than 0 and less than 10%. In some examples, said Differencing Constant can be greater than 0 and less than 10. In some examples, said CIP Reference Time can be greater than 0 and less than 10 days. The exemplary method can include the steps of comparing performance parameters before and after cleaning to ensure proper CIP and/or fouling identification. As such, the exemplary system and method can be used to identify filtration module failure modes and provide guidance for optimal cleaning to ensure efficient operation of the water filtration system.

[0022] In accordance with examples of the present disclosure, an exemplary system for determining a filter status is provided. The system includes a database configured to electronically store data, the data including past performance data of one or more water filtration elements. The system includes a processing device in communication with the database. The processing device is configured to receive as input the past performance data, and identify one or more data points within the past performance data indicative of a cleaning event for the water filtration elements. The processing device is configured to divide the past performance data into individual data segments, each of the individual data segments representing data of the past performance data in-between respective identified cleaning events. The processing device is configured to fit a mathematical function to each of the

individual data segments. The processing device is configured to identify a type of fouling occurring during each of the individual data segments based on the mathematical function fitted to the respective individual data segment.

[0023] In some examples, the processing device can be configured to normalize the past performance data to conditions at startup of the one or more water filtration elements before identifying the cleaning events. In some examples, the processing device can account for a variation of at least one of a feedwater temperature, a feedwater composition, or a feed pressure, when normalizing the past performance data.

[0024] In some examples, the processing device can be configured to identify and remove physically inconsistent data points from the past performance data before identifying the cleaning events. In some examples, the physically inconsistent data point is removed from the past performance data if at least one of the following conditions is not true: feed flow is greater than concentrate flow, the feed flow is greater than permeate flow, feed pressure is greater than concentrate pressure, and/or the feed pressure is greater than permeate pressure. In some examples, the physically inconsistent data point is removed from the past performance data if at least one of the following conditions is not true: feed flow is greater than concentrate flow, the feed flow is greater than permeate flow, feed pressure is greater than concentrate pressure, the feed pressure is greater than permeate pressure, the feed pressure is greater than pressure drop across the one or more water filtration elements, permeate conductivity is less than feed conductivity, the pressure drop across the one or more water filtration elements is less than or equal to a difference between the feed pressure and the concentrate pressure, and/or osmotic pressure of a feed stream is less than the feed pressure.

[0025] In some examples, the processing device can be configured to identify and remove statistical outlier data points from the past performance data before identifying the cleaning events. In such examples, identifying and removing the statistical outlier data points from the past performance data includes calculating a percentage change of a data point (y_t) from a previous data point (y_{t-1}), calculating a percentage change of a next data point (y_{t+1}) from the data point (y_t), comparing a previous percentage changes with a drop limit value, and identifying the data point (y_t) as an outlier if the percentage changes exceed the drop limit.

[0026] In some examples, identifying the cleaning events can include applying a differencing series method to normalized pressure drop (dP) and normalized permeate flow (Pf) from the past performance data. Applying the differencing series method can include the steps of (i) calculating a difference between the data point (y_t) and the previous data point (y_{t-1}) to generate a differencing series for the normalized pressure drop (dP) and the normalized permeate flow (Pf), (ii) calculating an average and standard deviations for the differencing series for the normalized pressure drop (dP) and the normalized permeate flow (Pf), (iii) comparing each value in the differencing series for the normalized pressure drop (dP) and the normalized permeate flow (Pf) to a sum of corresponding differencing series and a product of a differencing constant and a corresponding standard deviation of the differencing series, (iv) determining if a gap exists in the dataset, and (v) determining if the gap is wider than a CIP reference time.

[0027] In some examples, the processing device can be configured to analyze a coefficient of determination of the mathematical function and calculate derivatives of the mathematical function with respect to time. In such examples, the processing device can be configured to identify the type of fouling based on the derivatives of the coefficient of determination. In some examples, the one or more water filtration elements can be at least one of a reverse osmosis element, a nanofiltration element, or a hyperfiltration element. The system can include one or more sensors configured to detect and transmit data for pressure drop, salt passage, and permeate flow associated with each of the one or more water filtration elements for storage in the database as the past performance data.

[0028] In some examples, the past performance data can include pressure drop, salt passage, and permeate flow for each of the one or more water filtration elements. If no change in the pressure drop, salt passage, and permeate flow is detected, the processing device can identify a no fouling condition. If an increase in the pressure drop fits a 2nd order polynomial function, the processing device can identify the type of fouling as biofouling. In some instances of biofouling, the salt passage may increase and the permeate flow may decrease. If a decrease of the salt passage fits a 2nd order polynomial function, the processing device can identify the type of fouling as organic fouling. In some instances of organic fouling, the pressure drop may not change and the salt passage may decrease. If a steep increase in the pressure drop of first position elements (e.g., lead end filtration elements per FIG. 19) fits a 1st

order polynomial function, the processing device can identify the type of fouling as particulate fouling. In some instances of particulate fouling, the salt passage may increase and the permeate flow may decrease. In some instances, such effects can be found primarily in the lead elements. If a gradual increase in the pressure drop of tail position elements (e.g., tail end filtration elements per FIG. 19) fits a 1st order polynomial function, the processing device can identify the type of fouling as scaling. In some instances of scaling, the salt passage may increase and the permeate flow may decrease. In some instances, such effects can be found primarily in the tail elements. If an increase in the permeate flow fits a 1st order polynomial function and an increase in the salt passage fits a 1st order polynomial function, the processing device can identify the type of fouling as an integrity membrane damage event. In some instances of an oxidation or membrane damage event, the pressure drop may not change.

[0029] In some examples, the processing device can be configured to receive as input current performance data of the one or more water filtration elements as received from one or more sensors (e.g., multiple sensors can be installed in the same filtration element(s) and/or the sensors can be installed in multiple filtration elements within the installation to provide a more comprehensive fouling diagnostic), analyze the current performance data based on the previous analysis of the past performance data and the identification of the type of fouling occurring during each of the individual data segments, estimate a current type of fouling occurring at the water filtration elements, and/or output a recommendation for a cleaning procedure specific to the current type of fouling occurring at the water filtration elements. The collected data from the sensors can be filtration element specific to identify if certain conditions are occurring at the lead end or the tail end of the pressure vessel to assist in estimating the fouling type occurring. In some examples, the current performance data and/or the past performance data can be used to predict potential fouling occurring in the future (e.g., based on a repeating cycle of fouling during specific times of year and/or based on environmental conditions).

[0030] In accordance with examples of the present disclosure, an exemplary method for determining a filter status is provided. The method includes receiving as input to a system for determining a filter status past performance data of one or more water filtration elements. The system for determining the filter status includes a database configured to electronically store the past performance data, and a processing device in communication with the database.

The method includes identifying one or more data points within the past performance data indicative of a cleaning event for the one or more water filtration elements. The method includes dividing the past performance data into individual data segments, each of the individual data segments representing data of the past performance data in-between respective identified cleaning events. The method includes fitting a mathematical function to each of the individual data segments. The method includes identifying a type of fouling occurring during each of the individual data segments based on the mathematical function fitted to the respective individual data segment.

[0031] In accordance with examples of the present disclosure, an exemplary non-transitory computer-readable medium storing instructions for determining a filter status that are executable by a processing device is provided. Execution of the instructions by the processing device causes the processing device to receive as input to a system for determining a filter status past performance data of one or more water filtration elements. The system for determining the filter status includes a database configured to electronically store the past performance data, and the processing device in communication with the database. Execution of the instructions by the processing device causes the processing device to identify one or more data points within the past performance data indicative of a cleaning event for the one or more water filtration elements. This can be used to divide the past performance data into individual data segments, each of the individual data segments representing data of the past performance data in-between respective identified cleaning events. Execution of the instructions by the processing device causes the processing device to fit a mathematical function to each of the individual data segments. Execution of the instructions by the processing device causes the processing device to identify a type of fouling occurring during each of the individual data segments based on the mathematical function fitted to the respective individual data segment.

[0032] Any combination and/or permutation of examples is envisioned. Other objects and features will become apparent from the following detailed description considered in conjunction with the accompanying drawings. It is to be understood, however, that the drawings are designed as an illustration only and not as a definition of the limits of the present disclosure.