SUMMARY

[00014a] 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.

[00014b] 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, preferably further comprising identifying a type of scaling, or a no fouling, or a no scaling condition.

[00014c] 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, wherein the processing device preferably is further configured to identify a type of scaling, or a no fouling, or a no scaling condition.

[00015] 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, 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.

[00016] 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.

[00017] 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. Execution of the instructions by the processing device causes the processing device 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.

[00018] In some examples, for NF and RO filtration systems, 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 or Akaike Information Criterion (AIC) of dP to a 1st order polynomial is greater than 0.7, (b) the coefficient of determination or Akaike Information Criterion (AIC) of dP to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials fitted to dP is less than 0.3, (d) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 1st order polynomial is greater than 0.7, (e) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials fitted to Sp is less than 0.3, (g) the Akaike Information Criterion (AIC) of Pf to a 1st order polynomial is greater than 0.7, (h) the coefficient of determination or Akaike Information Criterion (AIC) of Pf to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination or Akaike Information Criterion (AIC) 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.

[00019] In some examples, for NF and RO filtration systems, 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 or Akaike Information Criterion (AIC) of dP to a 1st order polynomial is greater than 0.7, (b) the coefficient of determination or Akaike Information Criterion (AIC) of dP to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials fitted to dP is less than 0.3, (d) the coefficient of determination or Akaike

Information Criterion (AIC) of Pf to a 1st order polynomial is greater than 0.7, (e) the coefficient of determination or Akaike Information Criterion (AIC) of Pf to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials fitted to Pf is less than 0.3, (g) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 1st order polynomial is greater than 0.7, (h) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials fitted to Sp is less than 0.3, (j) dP increases rapidly over time in said data segment, (k) Pf decreases rapidly over time in said data segment, and/or (l) Sp increases rapidly with time in said data segment.

[00020] In some examples, for NF and RO filtration systems, 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 or Akaike Information Criterion (AIC) of dP to a 1st order polynomial is greater than 0.4, (b) the coefficient of determination or Akaike Information Criterion (AIC) of dP to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials is greater than 0.3, (d) the coefficient of determination or Akaike Information Criterion (AIC) of Pf to a 1st order polynomial is greater than 0.4, (e) the coefficient of determination or Akaike Information Criterion (AIC) of Pf to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials fitted to Pf is greater than 0.3, (g) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 1st order polynomial is greater than 0.4, (h) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination or Akaike Information Criterion (AIC) 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.

[00021] In some examples, for NF and RO filtration systems, the mode of filtration module failure in a data segment can be identified as chemical degradation (e.g., due to oxidation or the like) if at least one of the following conditions is met: (a) the coefficient of determination or Akaike Information Criterion (AIC) of Pf to a 1st order polynomial is greater than 0.7, (b) the coefficient of determination or Akaike In-

formation Criterion (AIC) of Pf to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for the 2nd order and 1st order polynomials fitted to Pf is less than 0.3, (d) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 1st order polynomial is greater than 0.7, (e) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials fitted to fitted to Sp is less than 0.3, (g) the coefficient of determination or Akaike Information Criterion (AIC) of dP to a 1st order polynomial is greater than 0.7, (h) the coefficient of determination or Akaike Information Criterion (AIC) of dP to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination or Akaike Information Criterion (AIC) 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.

[00022] In some examples, for NF and RO filtration systems, the mode of filtration module failure in a data segment can be identified as physical integrity failure (e.g., due to membrane damage, mechanical reasons, physical insult, or the like) if at least one of the following conditions is met: (a) the coefficient of determination or Akaike Information Criterion (AIC) of Pf to a 1st order polynomial is greater than 0.7, (b) the coefficient of determination or Akaike Information Criterion (AIC) of Pf to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for the 2nd order and 1st order polynomials fitted to Pf is less than 0.3, (d) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 1st order polynomial is greater than 0.7, (e) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials fitted to fitted to Sp is less than 0.3, (g) the coefficient of determination or Akaike Information Criterion (AIC) of dP to a 1st order polynomial is greater than 0.7, (h) the coefficient of determination or Akaike Information Criterion (AIC) of dP to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination or Akaike Information Criterion (AIC) 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 rapidly over time in said data segment, and/or (l) Sp increases rapidly over time in said data segment.

[00023] In some examples, for NF and RO filtration systems, 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 or Akaike Information Criterion (AIC) of Pf to a 1st order polynomial is greater than 0.4, (b) the coefficient of determination or Akaike Information Criterion (AIC) of Pf to a 2nd order polynomial is greater than 0.7, (c) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for the 2nd order and 1st order polynomials fitted to Pf is greater than 0.3, (d) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 1st order polynomial is greater than 0.4, (e) the coefficient of determination or Akaike Information Criterion (AIC) of Sp to a 2nd order polynomial is greater than 0.7, (f) the difference between the coefficient of determination or Akaike Information Criterion (AIC) values for 2nd order and 1st order polynomials fitted to fitted to Sp is greater than 0.3, (g) the coefficient of determination or Akaike Information Criterion (AIC) of dP to a 1st order polynomial is greater than 0.7, (h) the coefficient of determination or Akaike Information Criterion (AIC) of dP to a 2nd order polynomial is greater than 0.7, (i) the difference between the coefficient of determination or Akaike Information Criterion (AIC) 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.

[00024] In some examples, the term “drop limit” as used herein can be greater than 0 and less than 10%, or from 0 to 8%, 0 to 5%, 0 to 3%, or 0 to 2%. In some examples, the drop limit can be about, e.g., 0-10% inclusive, 0-9% inclusive, 0-8% inclusive, 0-7% inclusive, 0-6% inclusive, 0-5% inclusive, 0-4% inclusive, 0-3% inclusive, 0-2% inclusive, 0-1% inclusive, 1-10% inclusive, 2-10% inclusive, 3-10% inclusive, 4-10% inclusive, 5-10% inclusive, 6-10% inclusive, 7-10% inclusive, 8-10% inclusive, 9-10% inclusive, 1-9% inclusive, 2-8% inclusive, 3-7% inclusive, 4-6% inclusive, 2-6% inclusive, 4-8% inclusive, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, 10%, or the like. In some examples, the term “Differencing Constant” as used herein can be greater than 0 and less than 10, or from 0 to 8, 0 to 5, 0 to 3, or 0 to 2. In some examples, the Differencing Constant can be about, e.g., 0-10 inclusive, 0-9 inclusive, 0-8 inclusive, 0-7 inclusive, 0-6 inclusive, 0-5 inclusive, 0-4 inclusive, 0-3 inclusive, 0-2 inclusive, 0-1 inclusive, 1-10 inclusive, 2-10 inclusive, 3-10 inclusive, 4-10 inclusive, 5-10 inclusive, 6-10 inclusive, 7-10 inclusive, 8-10 inclusive, 9-10 inclusive, 1-9 inclusive, 2-8 inclusive, 3-7 inclusive, 4-6 inclusive, 2-6 inclusive, 4-8 inclusive, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or the like. In some examples, said the term “Membrane Cleaning Event (MCE) Reference Time” or “Cleaning-in-Place (CIP) Reference Time”

as used herein can be greater than 0 and less than 10 days, or from 0 to 8, 0 to 5, 0 to 3, or 0 to 2 days. In some examples, the MCE Reference Time can be about, e.g., 0-10 days inclusive, 0-9 days inclusive, 0-8 days inclusive, 0-7 days inclusive, 0-6 days inclusive, 0-5 days inclusive, 0-4 days inclusive, 0-3 days inclusive, 0-2 days inclusive, 0-1 days inclusive, 1-10 days inclusive, 2-10 days inclusive, 3-10 days inclusive, 4-10 days inclusive, 5-10 days inclusive, 6-10 days inclusive, 7-10 days inclusive, 8-10 days inclusive, 9-10 days inclusive, 1-9 days inclusive, 2-8 days inclusive, 3-7 days inclusive, 4-6 days inclusive, 2-6 days inclusive, 4-8 days inclusive, 1 day, 2 days, 3 days, 4 days, 5 days, 6 days, 7 days, 8 days, 9 days, 10 days, or the like. In some examples, MCE includes any type of membrane cleaning event (both chemical and physical) to restore filtration performance, such as flow reversal, backwash, chemical enhanced backwash, and/or chemical cleaning in-place. The exemplary method can include the steps of comparing performance parameters before and after cleaning to ensure proper cleaning 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.

[00025] For ultrafiltration (UF) and/or microfiltration (MF), the fouling type is correlated to the feed water condition and the operation routine details (see, e.g., FIG. 12C). Improvement can be made to the operation routine parameters to shift at least a part of the original irreversible fouling type towards a reversible fouling type. The evaluation and identification of fouling type by the system therefore provides direction for system operation optimization.

[00026] In some examples, for UF and/or MF filtration systems, the mode of filtration module failure in a data segment can be identified as cake formation fouling if TMP during filtration (TMP_F) increases linearly, while TMP during backwash (TMP_BW) and TMP during chemical enhanced cleaning (TMP_CEC) remain constant. In some examples, for UF and MF filtration systems, the mode of filtration module failure in a data segment can be identified as bio/organic fouling if TMP_F increases, while TMP_BW and TMP_CEC both increase with a linear or non-linear trend if oxidants or caustic are not used in the CEC. In some examples, for UF and MF filtration systems, the mode of filtration module failure in a data segment can be identified as inorganic fouling if TMP_F increases, while TMP_BW and TMP_CEC both increase with a linear or non-linear trend if acid is not used in the CEC. In some examples, for UF and MF filtration systems, the mode of filtration module failure in a data segment can be identified as chemical degradation if a gradual (weeks/months) increase is observed in membrane filtrate turbidity. In some examples, for UF and MF filtration systems, the mode of filtration module failure in a data segment can be

identified as physical integrity problem if a rapid (hours/days) increase is observed in membrane filtrate turbidity. Additionally, physical integrity problems can also be confirmed by an increase in silt density index (SDI), increase in pressure decay rate during integrity test, bubble presence in filtrate port during integrity test, increase in modified fouling index (MFI) and/or filtrate total suspended solids concentration.

[00027] As used herein, the term “cleanability” refers to the change, preferably the percentage change, of a primary indicator (for UF/MF this can be normalized TMP) before and after an i^{th} MCE compared with the change of the primary indicator before the i^{th} MCE and after the $(i1)^{th}$ MCE or the initial value when the overall operation starts. A higher cleanability means a better membrane performance recovery and can be used as secondary variable to help distinguish between fouling types. CEC cleanability between 60 to 95% can indicate cake formation fouling, while CEC cleanability below 60% can indicate either biological organic or inorganic fouling.

[00028] 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 conditions at startup, removing physically inconsistent data points from said dataset, removing statistical outliers from said dataset, identifying membrane cleaning events in the said dataset, dividing said dataset into a plurality of data segments between said membrane cleaning events, fitting mathematical functions to said data segments, analyzing the coefficient of determination of said mathematical functions, calculating derivatives of said mathematical functions with respect to time, and determining a type of fouling based on said derivatives and said coefficient of determination.

[00029] The filtration system includes at least one filtration module. The filtration module includes one or more of a reverse osmosis element, a nanofiltration element, or a hyperfiltration element. The collection of performance data can be performed by sensors installed in said filtration system. Normalization of said dataset can be performed to account for variation of said feedwater temperature, said feedwater composition, or feed pressure. Removal of outliers in said dataset can be performed by a statistical means including the steps of calculating a percentage change of a data point (y_t) from the previous datapoint (y_{t-1}), calculating a percentage change of the next data point (y_{t+1}) from said datapoint (y_t), comparing the previous percentage changes with a drop limit value, and identifying the datapoint (y_t) as an outlier if the percentage changes exceed said drop limit value.

[00030] Removal of physically inconsistent data points in said dataset can be performed by application of a set of criteria including one or more of the following: feed flow

[00033] 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.

[00034] 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. For reverse osmosis or nanofiltration, 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.

[00035] For ultrafiltration or microfiltration, in some examples, the removal of physically inconsistent data points in said dataset can be performed by application of a set of criteria including one or more of the following: feed pressure is equal to or greater than transmembrane pressure, transmembrane pressure across the filtration module is less than or equal to the difference between the feed pressure and the filtrate pressure, and feed turbidity is greater than filtrate turbidity. In some examples, the criteria also include the following: filtrate pressure must be greater than trans-membrane pressure.

[00036] 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 membrane 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.

[00037] 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.

[00038] In some examples, wherein the system is the ultrafiltration (UF) or the microfiltration (MF) system, identifying the cleaning events can include applying a differencing series method to a transmembrane pressure drop (TMP), a feed turbidity, and a permeability from the past performance data. Applying the differencing series method can include the steps of (i) calculating a difference between time values between the data point (t) and previous data points (t-x) to generate time differencing series; (ii) calculating the difference between the data point (yt) and previous data points (yt-x) to generate the differencing series for transmembrane pressure drop (TMP), feed turbidity, and permeability; (iii) comparing each value in the differencing series of time, transmembrane pressure drop (TMP), feed turbidity, and permeability to threshold values Backwash, CEB, and CIP MCE events; (iv) determining if comparison matches backwash MCE criteria; (v) determining if comparison matches CEB MCE criteria; and (vi) determining if comparison matches CIP MCE criteria.

[00039] In some examples, the processing device can be configured to analyze a prediction model, e.g., a coefficient of determination or Akaike Information Criterion (AIC) 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 or Akaike Information Criterion (AIC). In some examples, the one or more water filtration elements can be at least one of a reverse osmosis element, a nanofiltration element, a hyperfiltration element, an ultrafiltration element, or a microfiltration 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.

[00040] 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 rapid 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.

[00041] 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).

[00042] 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 Membrane Cleaning Events (MCE) and the type of filtration module failure modes based on the performance of the system in the inter and intra-MCE periods. In some examples that are related to UF or MF systems, MCE includes any type of membrane cleaning event (both chemical and physical) to restore filtration performance, such as flow reversal, backwash, chemical enhanced backwash, and/or chemical cleaning in-place. In other examples that are related to NF or RO, the MCE includes cleaning-in-place. The system provided herein can be used for ultrafiltration, microfiltration, nanofiltration and/or reverse osmosis systems to identify fouling, scaling, and/or membrane failure modes. In some examples, the system can be used to predict when the next cleaning should/will take place and to recommend the most suitable cleaning procedure.

[00043] 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 examples, the system can be used to anticipate cyclical and/or seasonal fouling, such that fouling event(s) can be minimized and/or avoided.

[00044] 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 conditions at startup, removing physically inconsistent data points from said dataset, removing statistical outliers from said dataset, identifying membrane cleaning events in the said dataset, dividing said dataset into a plurality of data segments between said membrane cleaning events, fitting mathematical functions to said data segments, analyzing a prediction model, for example the Akaike Information Criterion (AIC) or the coefficient of determination of said mathematical functions, calculating derivatives of said mathematical functions with respect to time, and determining a type of fouling based on said derivatives and said coefficient of determination or Akaike Information Criterion (AIC). (*See*, e.g.,, H. Akaike, "A new look at the statistical model identification," *IEEE Transactions on Automatic Control*, vol. 19, no. 6, pp. 716-723 (December 1974)).

[00045] The filtration system includes at least one filtration module. The filtration module includes one or more of an ultrafiltration element, a microfiltration element, a

reverse osmosis element, a nanofiltration element, and a hyperfiltration element. The collection of performance data can be performed by sensors installed in said filtration system. Normalization of said dataset can be performed to account for variation of said feedwater temperature, said feedwater composition, and/or feed pressure.

[00046] In some examples, removal of outliers in said dataset including reverse osmosis or nanofiltration data can be performed by a statistical means including the steps of calculating a percentage change of a data point (y_t) from the previous datapoint (y_{t-1}), calculating a percentage change of the next data point (y_{t+1}) from said datapoint (y_t), comparing the previous percentage changes with a drop limit value, and identifying the datapoint (y_t) as an outlier if the percentage changes exceed said drop limit value. A drop limit is defined here as a numerical value describing the maximum or minimum difference between two other numerical values that is tolerated by a system before an action is triggered. Alternatively, well known statistical methods such as the Inter-Quantile Range (IQR) method can be used to identify the datapoints that fall outside an acceptable limit (as set by or in the system).

[00047] In some examples, removal of outliers in said dataset including ultrafiltration or microfiltration data can be performed by the system using the method described herein. First the frequency of the data (e.g. every minute, every hour, every day) is compared against common guidelines for at least the following types of Membrane Cleaning Event timescales – air scouring (minutes), hydraulic backwash (minutes), chemically enhanced backwash (hours) and clean in place or CIPs (days). If the data is available at the hydraulic backwash timescale, a second dataset is generated by averaging said dataset so that it is now available at the chemically enhanced backwash timescale (hours). A third dataset is generated by averaging said dataset so that it is now available at the clean in place timescale (days). A first round of outlier detection can be performed on the third dataset by a statistical means including the steps of calculating a percentage change of a data point (y_t) from the previous datapoint (y_{t-1}), calculating a percentage change of the next data point (y_{t+1}) from said datapoint (y_t), comparing the previous percentage changes with a drop limit value, and identifying the datapoint (y_t) as an outlier if the percentage changes exceed said drop limit value. Alternatively, well known statistical methods such as the Inter-Quantile Range (IQR) method can be used to identify the datapoints that fall outside an acceptable limit.

[00048] A second round of outlier detection can be performed on the second dataset by a statistical means including the steps of calculating a percentage change of a data point (y_t) from the previous datapoint (y_{t-1}), calculating a percentage change of the next data point (y_{t+1}) from said datapoint (y_t), comparing the previous percentage changes with a drop limit value, and identifying the datapoint (y_t) as an outlier if the

MCEs. The method of determining the type of fouling or scaling depends on the process as described below.

[00057] 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. Fitting of a set of curves to said data segments can be performed using a statistical means.

[00058] 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.

[00059] 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.

[00060] 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.

BRIEF DESCRIPTION OF THE DRAWINGS

[00061] To assist those of skill in the art in making and using the system for determining filter status, reference is made to the accompanying figures, wherein:

[00062] FIG. 1 is a diagrammatic view of a traditional spiral wound filtration element;

[00063] FIG. 2 is a diagrammatic view of a portion of a typical feed spacer sheet of a traditional filtration element showing strand thinning and several geometric relationships;

[00064] FIG. 3 is a diagrammatic view of a typical separation occurring in a spiral wound reverse osmosis or nanofiltration element;