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Hydraulic fluid power – Interpolation method for particle count and filter test data

Transmissions hydrauliques – Méthode d'interpolation pour les données issues du comptage des particules et des essais du filtre

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Introduction

The 2016 version of ISO 11171 provides options for reporting particle size in either units of µm(c) or µm(b). While mathematical conversion of µm(b) sizes to µm(c) sizes is straightforward, there is no such universal means for converting particle concentrations or filter Beta Ratios. This is problematic when attempting to comply with contamination control and filter performance specifications given in integral units of µm(c) when data are in integral units of µm(b) corresponding to decimal point µm(c) sizes, or vice versa. For example, particle sizes of 4 µm(b), 6 µm(b), 14 µm(b) and 21 µm(b), correspond to sizes of 3,6 µm(c), 5,4 µm(c), 12,6 µm(c) and 18,9 µm(c), respectively. In the absence of a common interpolation method, otherwise acceptable fluid and filter products can be deemed unacceptable for use because of a discrepancy in the particle sizes reported. This document describes a recommended method for converting µm(b) data to µm(c) data and for interpolating particle concentration, Beta Ratio, and removal efficiency data. The resultant interpolated values can be used to convert cleanliness level or filter performance specifications and data from µm(b) to µm(c).

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Hydraulic fluid power – Interpolation method for particle count and filter test data

1 Scope

This document describes a recommended method for the interpolation of particle concentration and filter Beta Ratio data when results are not otherwise available at the desired particle sizes. It is applicable for assessing conformance with existing fluid cleanliness and filter Beta Ratio specifications whereby the specification and actual test results are provided in different units of particle size, for example, the specification is in µm(c), but the particle counts or Beta Ratio data are in units of µm(b).

This document is also applicable when particle sizes in specifications and available data use the same units of particle size, but do not correspond to exactly the same sizes, for example, when particle counts at 20 µm(c) are specified, but data was collected at 21 µm(c). This method allows interpolation to intermediate particle sizes within the range of existing data and does not permit extrapolation to particle sizes outside the range of available data.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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ISO 4406, *Hydraulic fluid power — Fluids — Method for coding the level of contamination by solid particles*

ISO 11171, *Hydraulic fluid power — Calibration of automatic particle counters for liquids*

ISO 16889, *Hydraulic fluid power — Filters — Multi-pass method for evaluating filtration performance of a filter element*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 4406, ISO 11171 and ISO 16889 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Background

In contamination control programmes, filter purchase decisions and quality control programmes, particle count and filter Beta Ratio data are compared to established benchmarks, such as fluid cleanliness specifications, filter performance specifications and historical data. Meaningful assessments can only be made if identical sizes are being compared. This became an issue with ISO 11171:2016. Historical data and specifications prior to 2016 were reported in size units of µm(c). Beginning in 2016, however, some chose to report size in units of µm(b) while others report in µm(c). The two units of particle size, µm(c) and µm(b), are mathematically related, but the corresponding values for particle concentration and Beta Ratio are not. The 10 % difference in particle size between the two units of particle size yields differences in the corresponding particle concentrations and Beta Ratios. These, in turn, can significantly impact critical contamination control decisions.

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As an example, consider whether or not to replace the oil in a hypothetical hydraulic system. In this example, it is assumed that the cleanliness level specification for its hydraulic fluid is an ISO 4406 code of 18/17/13. When a sample of the fluid was analyzed, particle concentrations of 5 135 particles/mL, 1 368 particles/mL, 98,3 particles/mL and 19,5 particles/mL at 4 µm(b), 6 µm(b), 14 µm(b), and 21 µm(b) respectively, were reported. Does this fluid meet the cleanliness specification, in which case it can continue to be used, or it is contaminated and must be replaced, and the corresponding costs of new fluid, downtime and lost productivity incurred? An uninformed user can incorrectly convert these µm(b) concentrations to ISO code values of 20/18/14 and conclude that the fluid was contaminated. This would be an expensive mistake. ISO 4406 stipulates that the code applies to particle sizes of 4 µm(c), 6 µm(c) and 14 µm(c), not µm(b). Particle sizes of 4 µm(b), 6 µm(b), 14 µm(b) and 21 µm(b) sizes correspond to 3,6 µm(c), 5,4 µm(c), 12,6 µm(c) and 18,9 µm(c), respectively. The µm(b) concentrations appear higher than those concentrations found for µm(c) sizes of the same numerical value. Ideally, the sample should be re-analyzed using an Automatic Particle Counter (APC) calibrated in µm(c), but this is often impossible or impractical. A similar problem occurs whenever specifications and data (e.g. particle concentrations, ISO codes, or filter Beta Ratios) are in different units of particle size. Thus, there is a need for a reliable method for converting µm(b) to µm(c), and then for interpolating to obtain data at the desired particle sizes for contamination control decisions.

The constrained cubic spline method of interpolation that is used in ISO 11171:2020 to relate particle concentrations to threshold settings and particle sizes to create calibration curves for APCs, may be used to interpolate particle concentration and filter Beta Ratio data. Traditional cubic spline interpolation starts with a series of known data points, the training data set, and interpolates between them according to the following rules:

— The cubic spline curve passes through all of the known points;

— The curve connecting consecutive points are a third-degree polynomial;

— The first derivative of the curves on each side of a known point are equal;

— The second derivative of the curves on each side of a known point are equal; and

— Boundary conditions are established for the minimum and maximum values of x.

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While traditional cubic spline interpolation produces a smooth curve, its usefulness for purposes of interpolating particle concentration and Beta Ratio data is compromised by a tendency to overshoot between node points. In contrast, the constrained cubic spline method prevents overshooting and improves accuracy by sacrificing a little in terms of smoothness. This is accomplished by eliminating the requirement for second derivatives to be equal. Instead, the first order derivatives on each side of a point are specified. Since accuracy is paramount in particle counter calibration, the constrained cubic spline method has been adopted in ISO 11171:2020. The same rationale applies to other fluid power cleanliness and filter performance applications.

Contamination control decisions should be made using data obtained at the actual sizes defined in specifications or standards, but this is not always possible or practical. For example, a standard can specify particle size in units of µm(c), but the available particle count or Beta Ratio data can be from an APC calibrated to ISO 11171:2016 and reported size in units of µm(b). Similarly, a specification can use µm(b) sizes from the obsolete ISO 11171:2016, but the available data can be from an APC calibrated to ISO 11171:2020 which reports size only in units of µm(c). In such cases, the constrained cubic spline method of interpolation is recommended for estimating particle concentrations and Beta Ratios as a function of particle size, when data is not available at the specific sizes of interest. It should be noted that the accuracy of the resultant interpolation is dependent upon the quality of the original data. Accuracy is sacrificed when the input data contains errors, when there is too little data available for accurate interpolation, or when the available sizes skew the interpolation.

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5 Interpolation of particle concentration and Beta Ratio data

Meaningful comparisons of particle concentrations and Beta Ratios can only be made if all data is reported in the same units of particle size. ISO 11171:2020 standardized on μm(c) as the only acceptable unit for reporting particle size; hence it is recommended that specifications and historical data utilizing μm(b) sizes be converted to their corresponding μm(c) sizes. The interpolation of μm(b) to μm(c) data involves the following steps:

1) Mathematical conversion of μm(b) sizes to μm(c);

2) Constrained cubic spline interpolation of the data using the resultant μm(c) sizes;

3) Visual validation of the interpolated results; and

4) Determination of interpolated particle concentrations or Beta Ratios for μm(c) at the particle sizes of interest.

This may be performed manually or using the spreadsheet provided at the following URL link to N425 Data Interpolation for Contamination Control Applications: https://standards.iso.org/iso/tr/4808/ed-1/en/. The link accesses an Excel file containing three spreadsheets: *Instructions*, *Interpolation - Concentration* for interpolation of particle concentration data and *Interpolation - Beta Ratio* for interpolation of Beta Ratio and filter removal efficiency data. Regardless of whether interpolation is performed manually or using the spreadsheet, the constrained cubic spline interpolation method described in this section is preferred over the traditional cubic spline or other interpolation methods. Data for at least 3, but ideally 6 or more particle sizes is needed for the training data set.

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The first step of the interpolation process is to convert μm(b) sizes to μm(c) by multiplying the μm(b) sizes by a factor of 0,898, as defined in ISO 11171:2016. For example, 4 μm(b) corresponds to 3,59 μm(c); 6 μm(b) corresponds to 5,39 μm(c); 14 μm(b) corresponds to 12,57 μm(c); etc. This can be performed using either the *Interpolation - Concentration* or *Interpolation - Beta Ratio* spreadsheets by entering the known μm(b) particle sizes in column A and the corresponding particle concentrations or Beta Ratios in column B. The data is entered in order of increasing particle size using only paired data, i.e. for each size, there must be a corresponding concentration or Beta Ratio. The spreadsheet displays the μm(c) sizes corresponding to each μm(b) size in the light grey "Converted particle size" column of the spreadsheet and plots the data in μm(c) sizes on the graph in the spreadsheet as black squares. In most cases, integral μm(b) sizes correspond to non-integral μm(c) sizes. The μm(b) to μm(c) conversion equation is valid only for particle sizes less than or equal to 38 μm(c). For larger sizes, the numerical values of μm(b) and μm(c) sizes are equivalent, and the spreadsheet automatically adjusts this. In addition to converting μm(b) sizes to μm(c), the *Interpolation-Beta Ratio* spreadsheet also converts and displays Beta Ratio data as removal efficiencies.

Interpolation of data for intermediate sizes should be performed using the constrained cubic spline method and the previously calculated μm(c) sizes with corresponding particle concentrations or Beta Ratios. Referring to the spreadsheets, values for interpolated intermediate μm(c) sizes over the range of the original data are automatically calculated and displayed in the dark grey "Interpolation Curve" columns. The *Interpolation-Concentration* spreadsheet plots the interpolation curve on the graph as a red line. The *Interpolation-Beta Ratio* spreadsheet plots the interpolation curves on two different graphs, one for Beta Ratio data and one from removal efficiency data. In both cases, the interpolation curve is displayed as a red line.

The next step of the interpolation process is to visually inspect the plotted interpolation curve for evidence of abnormalities. It is desirable, but not mandatory, that the interpolation curve be based upon 6 or more data points, evenly spread over and bracketing the μm(c) particle sizes of interest. The curve should appear to be smooth, monotonic, and without sharp inflections. Deviations from this appearance, e.g. abrupt changes in slope, oscillatory behaviour or apparent overshooting of the data,

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are usually the result of shortcomings in the original data set. Examples of such shortcomings include, but are not limited to:

— too few data points,

— biased spacing of the available sizes,

— errors at one or more data points, and

— inclusion of data for particle sizes between 30 µm(b) and 38 µm(b)

The latter is an artefact of ISO 11171:2016. This is the transitional size range between NIST certified sizes and other methods of defining size. With this previous version of ISO 11171, users had the option of using latex or uncertified United States National Institute of Standards and Technology Standard Reference Material® (NIST SRM) 2806 sizes for calibration, which could result in an inflection point. In some other cases, an apparent deviation from the expected behaviour can reflect the true behaviour of the system, but the user is advised to attempt to verify this by obtaining data at additional sizes and reperforming the interpolation before accepting this conclusion. The interpolation should be considered validated if any observed deviations are deemed insignificant for the intended purpose of the interpolated data.

The final step is to determine interpolated values for particle concentrations or Beta Ratios at specific intermediate sizes using the previously validated interpolation. Using the appropriate spreadsheet, enter the values of the desired µm(c) sizes in the “Particle Size” column of the “Interpolated µm(c) data” portion of the spreadsheet. The interpolated values will be displayed in the adjacent blue columns and plotted as red circles on the graphs. The constrained cubic spline method cannot be used to extrapolate outside the limits of the data. If a desired size is outside the range of the data, a value of 0 is displayed by the spreadsheet for the interpolated concentration, Beta Ratio or removal efficiency and the corresponding cell is displayed in black.

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The method described in the preceding paragraphs should be used to convert µm(b) data to µm(c) data and to interpolate particle concentration, Beta Ratio, and removal efficiency data. Interpolated values obtained in this manner may also be used to convert cleanliness level or filter performance specifications and data from µm(b) to µm(c).

6 Example of interpolation of particle concentration data

To illustrate the use of the constrained cubic spline interpolation method for contamination control, consider a hydraulic system with a fluid cleanliness specification of ISO 4406 code 18/16/13. An oil sample collected from the system yielded the data shown in Table 1.

Table 1 — Particle count data from system reported in units of µm(b)

Particle size	**Particle concentration**
µm(b)	Particles/mL > indicated size
4	2 824
6	752
10	182
14	54,1
21	10,7
30	2,16

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The *Interpolation - Concentration* spreadsheet will be used for this purpose. An ISO code specification of 18/16/13 means that the fluid must contain fewer than 2 500 particles/mL larger than 4 µm(c), 640 particles/mL larger than 6 µm(c), and 80 particles/mL larger than 14 µm(c), The particle count data, however, is in units of µm(b). ISO 4406 only uses particle size in units of µm(c). To determine whether the fluid is sufficiently clean for continued use, the available µm(b) data must be converted to µm(c) and interpolated. Using the spreadsheet, the data from Table 1 is entered in the first two columns (columns A and B), as shown in Table 2. The third column, column C, displays the corresponding µm(c) sizes.

Note that the µm(c) sizes are not integral and none correspond to the sizes required by ISO 4406.

The interpolation curve is displayed in red on the plot, and the original data are displayed as black squares, as shown in Figure 1. The interpolation curve appears smooth and monotonic. Any suspected inflection points that exist are far less than 1 ISO code unit, i.e. a doubling in concentration and insignificant for purposes of the specification. Having visually validated the interpolation curve, the ISO code sizes of 4 µm(c), 6 µm(c) and 14 µm(c) are entered into Particle Size column H and yielding interpolated concentrations of 2 184,07 particles/mL larger than 4 µm(c), 595,51 particles/mL larger than 6 µm(c), and 38,99 particles/mL larger than 14 µm(c). These concentrations correspond to an ISO 4406 code of 18/16/12, within the acceptable fluid cleanliness specifications of the system.

Table 2 — Completed spreadsheet used in fluid cleanliness assessment example

Original µm(b) data		**Converted**		**Interpolation curve**			**Interpolated µm(c) data**	
Particle size	**Particle concentration**	**particle size**		**Intermediate size**	**Interpolated value**		**Particle size**	**Particle concentration**
µm(b)	Particles/ mL > size	µm(c)		µm(c)	Particles/ mL > size		µm(c)	Particles/ mL > size
4,0	2 824,00	3,59		3,59	2 824,00		4,0	2 184,07
6,0	752,00	5,39		3,83	2 45,26		6,0	595.51
10,0	182,00	8,98		4,06	2 094,87		14,0	38,99
14,0	54,10	12,57		4,29	1 756,18			
21,0	10,70	18,86		4,53	1 448,56			
30,0	2,16	26,94		4,76	1 182,36			

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