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An American National Standard

Standard Test Method for Predicting the Borderline Pumping Temperature of Engine Oil[1]

This standard is issued under the fixed designation D 3829; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

[1] This test method is under the jurisdiction of ASTM Committee D-2 D02 on Petroleum Products and Lubricants and is the direct responsibility of Subcommittee D02.07.0C on Flow Properties. Low Temperature Rheology of Non-Newtonian Fluids.

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1. Scope

1.1 This test method covers the prediction of the borderline pumping temperature (BPT) of engine oils through the use of a 16-h cooling cycle over the temperature range from 0 to −40°C.

1.2 Applicability to petroleum products other than engine oils has not been determined.

1.3 This test method uses the millipascal (mPa·s), as the unit of viscosity. For information, the equivalent centipoise unit is shown in parentheses.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Terminology

2.1 *Definitions:*

2.1.1 *apparent viscosity*—the ratio between the applied shear stress and rate of shear. It is sometimes called the coefficient of dynamic viscosity. This value is thus a measure of the resistance to flow of the liquid. The SI unit of determined viscosity is the pascal second (Pa·s). The centipoise (cP) is one millipascal second (mPa·s) and is often used. obtained by use of this test method.

2.1.2 *Newtonian oil or fluid*—an oil or fluid that at a given temperature exhibits a constant viscosity at all shear rates or shear stresses.

2.1.3 *non-Newtonian oil or fluid*—an oil or fluid that at a given temperature exhibits a viscosity that varies with changing shear stress or shear rate.

2.1.4 *apparent viscosity*—the determined viscosity obtained by use of this test method.

2.1.5 *shear rate*—the velocity gradient in fluid flow. For a Newtonian fluid in a concentric cylinder rotary viscometer in which the shear stress is measured at the inner cylinder surface (such as the apparatus being described), and ignoring any end effects, the shear rate is given as follows:

$$G_r = \frac{2\Omega R_s^2}{(R_{s2} - R_r^2)} \quad (1)$$

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$$G_r = \frac{4\pi R_s^2}{t(R_s^2 - R_r^2)} \quad (2)$$

where:
G_r = shear rate at the surface of the rotor in reciprocal seconds, s^{-1},
Ω = angular velocity, rad/s,
R_s = stator radius, mm,
R_r = rotor radius, mm, and
t = time in seconds for one revolution of the rotor.

For the specific apparatus being described in 5.1.1,

$$G_r = \frac{63}{t} \quad (3)$$

2.1.65 *shear stress*—the motivating force per unit area for fluid flow. Area is the area under shear. For the rotary viscometer being described, the rotor surface is the area under shear.

$$T_r = 9.81M(R_o + R_t) \times 10^{-6} \quad (4)$$

$$S_r = \frac{T_r}{2\pi R_r^2 h} \times 10^9 \quad (5)$$

where:

T_r = torque applied to rotor, N·m,
M = applied mass, g,
R_o = radius of the shaft, mm,
R_t = radius of the thread, mm,
S_r = shear stress at the rotor surface, Pa, and
h = height of the rotor, mm.

For the dimensions given in 5.1.1,

$$T_r = 31.7M \times 10^{-6} \quad (6)$$

$$S_r = 3.5M \quad (7)$$

2.1.6 *viscosity*—the ratio between the applied shear stress and rate of shear. It is sometimes called the coefficient of dynamic viscosity. This value is thus a measure of the resistance to flow of the liquid. The SI unit of viscosity is the pascal second (Pa·s). The centipoise (cP) is one millipascal second (mPa·s) and is often used.

2.2 *Definitions of Terms Specific to This Standard:*

2.2.1 *borderline pumping temperature*—the maximum temperature at which the critical yield stress or critical viscosity occurs, whichever is the higher temperature.

2.2.2 *calibration oils*—those oils for establishing the instrument's reference framework of apparent viscosity versus speed from which the apparent viscosities of test oils are determined. Calibration oils, which are essentially Newtonian fluids, are available commercially, and have an approximate viscosity of 30 000 mPa·s (30 000 cP) at −20°C.[2]

~~2.2.2 *test oil*—any oil for which the apparent viscosity and yield stress are to be determined by use of the test method under description.~~

2.2.3 ~~*yield stress*~~*critical viscosity*—the maximum viscosity at a defined shear ~~stress required~~ rate to ~~initiate flow. For all Newtonian fluids and some non-Newtonian fluids, yield stress is zero. Some engine oils have a yield stress that is a function~~ allow adequate flow of ~~their low-temperature cooling rate, soak time, and temperature.~~ oil to the oil pump in an automotive engine. A higher viscosity can cause failure to maintain adequate oil pressure through the limiting of flow through the oil screen or oil inlet tubes.

2.2.4 *critical yield stress*—the maximum yield stress that allows oil to flow to the inlet oil screen in an automotive engine. With a higher yield stress, air may be drawn into the pump and cause failure to maintain adequate oil pressure through air-binding of the pump.

2.2.5 ~~*critical viscosity*~~*test oil*~~—the maximum viscosity at a defined shear rate to allow adequate flow of~~—any oil ~~to~~ for which the ~~oil pump in an automotive engine. A higher~~ apparent viscosity ~~can cause failure~~ and yield stress are to ~~maintain adequate oil pressure through the limiting~~ be determined by use of ~~flow through~~ the ~~oil screen or oil inlet tubes.~~ test method under description.

2.2.6 ~~*borderline pumping temperature*~~*yield stress*—the ~~maximum temperature at which the critical~~ shear stress required to initiate flow. For all Newtonian fluids and some non-Newtonian fluids, yield stress ~~or critical viscosity occurs, whichever~~ is ~~t~~ zero. Some engine oils have a yield stress that is a function of their low-temperature cooling rate, soak time, and temperature.

3. Summary of Test Method

3.1 An engine oil sample is cooled from 80°C to the desired test temperature at a nonlinear programmed cooling rate over a 10-h period and held at the test temperature for the remainder of a 16-h period. After completion of the soak period, two standard torques of increasing severity are applied to the rotor shaft and the speed of rotation in each case is measured. From the results at three or more temperatures, the borderline pumping temperature is determined.

3.2 Alternatively, for some specification or classification purposes it may be sufficient to determine that the BPT is less than a certain specified temperature.

4. Significance and Use

4.1 Borderline pumping temperature is a measure of the lowest temperature at which an engine oil can be continuously and adequately supplied to the oil pump inlet of an automotive engine.

5. Apparatus

5.1 *Mini-Rotary Viscometer,*[2] consisting of one or more viscometric cells including a calibrated rotor-stator assembly, which are contained in a temperature-controlled aluminum block.

5.1.1 The viscometric cell has the following nominal dimensions:

Diameter of rotor	17.0 mm
Length of rotor	20.0 mm
Inside of diameter of cup	19.0 mm
Radius of shaft	3.18 mm
~~Radius of string~~	~~0.05 mm~~
Radius of string	0.1 mm

5.2 *Thermometers,*[2] for measuring temperature of the block. Two are required, one graduated from at least +70 to 90°C in 1°C subdivisions, the other with a scale from at least −36 to +5°C in 0.2°C subdivisions.

5.3 A means of lowering the temperature to the predetermined test temperature at a controlled, nonlinear rate.

5.4 *Circulating System,*[2] for supplying suitable liquid coolant to the block as needed. Methanol is a suitable coolant. One should observe toxicity and flammability precautions that apply to the use of methanol. The circulating system must be capable of maintaining test temperature over a 16-h test period. If methanol is leaking from the system, discontinue the test and repair the leak before continuing.

5.5 *Chart Recorder*, to verify that the correct cooling curve is being followed, it is recommended that a chart recorder be used to monitor the block temperature.

6. Reagents and Materials

6.1 *Low Cloud-Point, Newtonian Oil,*[2] of approximately 30 Pa·s (30 000 cP) viscosity at −20°C for calibration of the viscometric cells.

6.2 *Methanol*, commercial or technical grade of dry methanol is suitable for the cooling bath.

6.3 *Oil Solvent*, commercial Heptanes or similar solvent is suitable.

6.4 *Acetone*, technical grade of acetone is suitable provided it does not leave a residue upon evaporation.

7. Sampling

7.1 A representative sample of test oil free from suspended solid material and water is necessary to obtain valid results. If the sample in its container is received below the dew-point temperature of the room, allow to warm to room temperature before opening.

8. Calibration and Standardization

8.1 Calibration is required for the temperature dial on the panel.

8.1.1 Place calibrated thermometer in position (see assembly instructions) and turn the RESET dial fully counterclockwise.

8.1.2 Set the dial at 100 and allow to cool to control temperature. Allow approximately 30 min for temperature equilibrium to be established.

8.1.3 Record the temperature.

8.1.4 Repeat 8.1.3 and 8.1.4 for dial settings of 200, 300, 500, 700, and 900 or until −37°C has been reached.

8.1.5 On one- or two-cycle semilog graph paper, plot log (reading) versus temperature (°C) to establish calibration curve. See Fig. 1.

8.2 The calibration of each viscometric cell (viscometer constants) can be determined with the viscosity standard and the following procedure at −20 ± 0.2°C.

8.2.1 Use steps 9.1.1-9.1.5.

8.2.2 Set the temperature-control, ten-turn dial to correspond to −20°C and turn switch to cool.

8.2.3 Allow to soak at −20 ± 0.2°C for at least 1 h, making small temperature adjustments, if necessary, to maintain the test temperature.

8.2.4 At the end of the soak period record the temperature reading (test temperature), and remove the cover of the viscometer cell.

8.2.5 Proceed to steps 9.2.1-9.2.3.

8.2.6 Place a 150-g mass on the string in accordance with instructions in 9.3.1.

8.2.7 Repeat 8.2.5 and 8.2.6 for each of the remaining cells, taking the cells in order from left to right.

8.2.8 Calculate the viscometer constant for each cell (rotor/stator combination) with the following equation:

$$C = \frac{\eta_o}{Mt} \tag{8}$$

~~[2] Available from~~

[2] The sole source of supply of the apparatus known to the committee at this time is Cannon Instrument Co., P.O. Box 16, State College, PA 16801. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

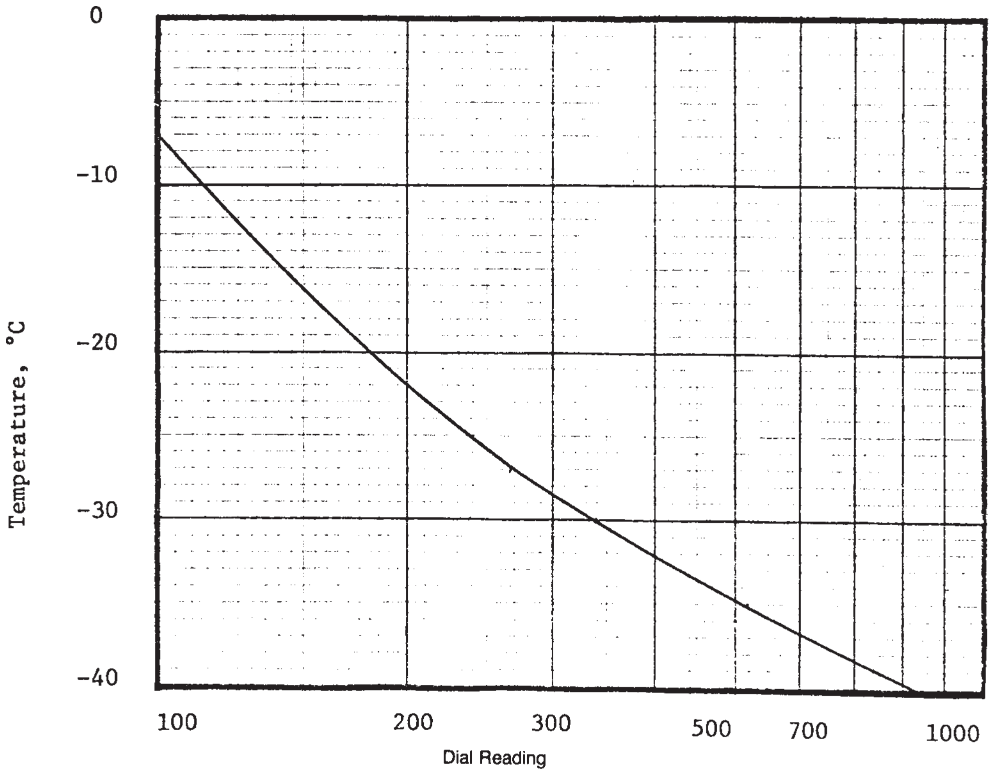

FIG. 1 Typical Dial Calibration

where:

η_o = viscosity of the standard oil, mPa·s (cP) at −20°C,
C = cell constant, Pa (N/m^2 g),
M = applied mass, g, and
t = time in seconds for one revolution.

8.3 It is essential that the ice point of the calibrated thermometer be measured initially and periodically thereafter, and that the corrections be adjusted to conform with any change in the ice point.

8.4 Check the rate of cooling periodically to ensure a standard cooldown rate. The reset knob should rotate one complete revolution each hour for 10 h, but must not turn during the final 6-h soak period. The approximate temperature of the thermometer at hourly intervals is shown in Table 1 for cooling to a final temperature of −20°C, and should be attained within the limits shown in the table. A chart recorder may be used to monitor the temperature cool-down rate.

9. Procedure

9.1 *Test Sample and Viscometric Cell Preparation*:

9.1.1 With the viscometric cells clean and at ambient temperature, remove the nine rotors.

9.1.2 Place a 10 ± 1 mL oil sample in each cup.

9.1.3 Install the rotors in the proper stators and install the upper pivots.

9.1.4 Place one of the loops in the 700-mm long string over the crossarm at the top of the rotor shaft and wind all but 200 mm of the length of the string around the shaft. Loop the remaining end of the string over the top bearing cover. Make sure that the marked (red) end of the crossarm at the top of the rotor shaft points to the rear of the viscometer unit.

9.1.5 Place the housing cover in place to minimize the formation of frost on the cold metal parts exposed to air. If frost formation persists, a small container of a desiccant such as Drierite may be placed under the cover to absorb excess moisture.

TABLE 1 Ten-Hour Cooling Temperatures—Time for ~~Cooling to −20°C~~

~~Time, h~~	~~Temperature, °C~~	~~Time, h~~	~~Temperature, °C~~
Time, h	Temperature, °C	Time, h	Temperature, °C
1	2.3 ± 5.0	6	−16.7 ± 0.7
2	−5.9 ± 3.0	7	−17.8 ± 0.5
3	−10.4 ± 2.0	8	−18.7 ± 0.3
4	−13.2 ± 1.5	9	−19.4 ± 0.3
5	−15.2 ± 1.0	10	−20.0 ± 0.3

9.1.6 Turn the switch to HEAT to preheat the oil sample to 80 ± 3°C. The rate of increase of temperature is approximately 3°C/min. Hold the temperature of the oil at this temperature for 2 h to allow solution of any material not in true solution at room temperature.

9.1.7 Set the temperature control ten-turn dial to the test temperature desired (see Section 8), turn the reset knob to the extreme clockwise position, turn the switch to COOL, and record the time as start of 16-h conditioning period.

9.1.8 At the end of the 16-h conditioning period record the thermometer reading (test temperature) and remove the cover of the viscometer cell noting any calibration corrections to the thermometer reading. Even if the anticipated test temperature has not been precisely achieved, do not adjust the temperature control. Proceed to measure yield stress and viscosity at that temperature (9.2 and 9.3).

9.2 *Measurement of the Yield Stress* :

9.2.1 Beginning with the cell farthest to the left of the instrument, run each cell in turn with the following procedure.

9.2.2 Align the pulley wheel with the shaft of the cell to be run, such that the string hangs past the front of the housing. Make sure that the weights will clear the edge of the bench during testing.

9.2.3 Remove the string from the upper bearing support and place it over the pulley wheel carefully so as not to disturb the test cell (that is, do not allow the rotor shaft to turn). Put the brass block with the two marking rods in front of the viscometer cell, aligned to facilitate noting when the red-marked rotor crossarm passes the "front" of the viscometer cell.

9.2.4 Carefully (so as not to disturb the gel structure, if any) attach a 10-g mass to the string. If no rotation can be discerned (approximately 10° in 15 s) add additional 10-g weights (in each case waiting about 15 s to see if rotation occurs). This rotation is equivalent to a 0.5-mm rotation at the circumference of the pulley wheel.

9.2.5 If rotation occurs with the 30-g mass, the yield stress of the test sample at this test temperature is less than the critical yield stress. Proceed to 9.3.

9.2.6 If rotation occurs with the 40-g mass, but not the 30-g mass, the yield stress is defined as the critical yield stress. Proceed to 9.3.

9.2.7 If rotation occurs only with 50-g mass or more, record the highest mass without rotation and proceed to 9.3.

9.3 *Measurement of Viscosity*:

9.3.1 Attach the 150-g mass to the string. When discernible rotation occurs, start the timer when the red end of the crossarm of the rotor shaft passes the aligned marking rods. Measure the time required for three revolutions unless the first half-revolution after start of timing requires more than 1 min, in which case record the time for one revolution.

9.4 Repeat 9.2-9.3.1 for each of the remaining cells, taking the cells in order from left to right.

9.4.1 After all of the cells have been completed, turn off the COOL switch and turn on the HEAT switch to warm the viscometric cells to room temperature or to a somewhat higher temperature.

9.4.2 Remove the upper rotor pivots and the rotors. The upper bearing support may have to be removed to remove the rotors.

9.4.3 Using vacuum, remove the oil samples and rinse the cells with an oil solvent several times, and acetone twice. Use vacuum to remove the solvent from the cells after each rinse and allow the acetone to evaporate to dryness after the final rinse.

9.4.4 Clean the rotors in a similar manner.

9.5 To calculate the BPT (Section 10), it is necessary to determine the temperature at which (*1*) the yield stress is the critical yield stress or (*2*) the apparent viscosity measured with a 150-g mass is 30 Pa·s (30 000 cP), whichever occurs at the higher temperature. The procedure in Section 9 must be repeated at more than one temperature.

9.5.1 A test sample can have unusual behavior such that the critical yield stress may be observed at two different temperatures. To ensure that a higher BPT does not exist, the yield stress for the sample must be (if it has not already previously been) measured at (*1*) 12 ± 2°C higher than the indicated BPT and (*2*) 7 ± 2°C higher than the indicated BPT.

9.6 Alternatively, if it is only desired to determine that the BPT occurs below a certain specified temperature, one must determine the viscosity and yield stress at that temperature and if these are below the critical BPT limits then determine the yield stress at 7 ± 2°C and 12 ± 2°C above the specified temperature.

10. Calculations and Determination of BPT

10.1 *Yield Stress Calculation and Air Binding BPT*:

10.1.1 If rotation was observed for the 30-g mass, yield stress will be less than 105 Pa (N/m^2) and can be assumed to be zero for purposes of this work.

10.1.2 If a mass greater than 30 g was needed to start rotation, calculate the shear stress for the largest mass that did not cause rotation, using Eq 7 of 2.1.65. For purposes of this work, the shear stress calculated in this way is designated the yield stress.

10.1.3 The BPT at which failure to pump by "air binding" of the pump occurs at a critical yield stress of 105 Pa (N/m^2), which corresponds to a 30-g mass.

10.1.3.1 A plot of yield stress versus temperature may be constructed so as to extrapolate or interpolate to 105 Pa (N/m^2) for the purpose of estimating the temperature at which to repeat Section 9.

10.1.4 The temperature rounded to the nearest 0.5°C corresponding to a yield stress of 105 Pa (N/m^2) is the BPT for air binding failure mode.

10.2 *Viscosity Calculation and Viscosity BPT*:

10.2.1 Calculate the apparent viscosity of the oil at each temperature with the following equation:

$$\eta_a = MtC \quad (9)$$

where:

η_a = apparent viscosity, mPa·s (cP),
M = applied mass, g (150 g),
t = time in seconds for one revolution of the rotor, and
C = viscometer constant for the specific viscometer cell and rotor combination used.

10.2.2 From a plot of apparent viscosity versus temperature, interpolate to determine the temperature at an apparent viscosity of 30 Pa·s. This temperature is the BPT for a "flow-limiting" failure mode. Do not extrapolate data; if necessary, repeat Section 9 at another temperature.

10.3 Select the higher of the two temperatures in 10.1.4 and 10.2.2 rounded to the nearest 0.5°C and the mode of failure (flow-limited or air-binding) as the borderline pumping temperature.

11. Report

11.1 Report the predicted BPT as determined in 10.1-10.3.

11.2 Alternatively it may be desirable to report that the BPT is below a certain specified temperature.

12. Precision and Bias [3]

12.1 The precision of this test method as obtained by statistical examination of interlaboratory test results of 13 oils whose BPT varied from −14.5 to −36°C is as follows:

12.2 *Repeatability*—The difference between successive test results obtained by the same operator with the apparatus under constant operating conditions on identical test materials, would in the long run, in the normal and correct operation of this test method exceed 1.3°C only in one case in twenty.

12.3 *Reproducibility*—The difference between two single and independent test results, obtained by different operations working in different laboratories on identical test material, would in the long run, in the normal and correct operation of this test method, exceed 3.2°C only in one case in twenty.

12.4 *Bias*—No justifiable statement can be made on the bias of the procedure described above, since all determinations are relative to the calibration fluid.

13. Keywords

13.1 borderline pumping temperature; viscosity; yield stress

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[3] Supporting data ~~are available from~~ have been filed at ASTM International Headquarters~~. R~~ and may be obtained by requesting Research Report RR:D02-1107.