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Viscosity & Viscosity Modifiers

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Outline

- Viscosity
  - Definition & Terminology
  - Temperature Dependence
- Viscosity Modifiers
  - Function
  - Thickening Efficiency (TE)
  - Shear-Thinning
  - Types/Chemistry
- Pour Point Depressants (PPD)
- SAE Viscosity Grades
- Appendix
  - Viscosity measurement methods

Viscosity

Viscosity

- Dynamic viscosity is resistance to flow of a fluid
- Defined as shear stress divided by shear rate
  - (how hard you push it divided by how fast it slides)
  - Units of dynamic viscosity:
    - Pascal seconds (Pa-s)
    - mPa-s = 1cP (CentiPoise)
- Dynamic viscosities are usually measured under high shear conditions:
  - For example, the cone on plate or cylinder viscometer
- Kinematic viscosity is the dynamic viscosity divided by the fluid density.
  - The physical principle of measurement is based on the rate at which a fluid flows under gravity through a capillary tube.
  - Usually measured under low shear conditions.
  - Units of kinematic viscosity:
    - mm^2/s
    - Common Unit: CentiStoke (cSt) = mm^2/s

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What is the Optimal Viscosity?

- Metal on metal contact leads to high energy losses and surface wear
- Oil film between metal surfaces reduces energy losses
  - Oil provides less resistance to movement than metal
- Sufficient viscosity is needed to form the film
- Viscosity should be high enough to form the protective film, but low enough to not give excessive energy losses within the fluid

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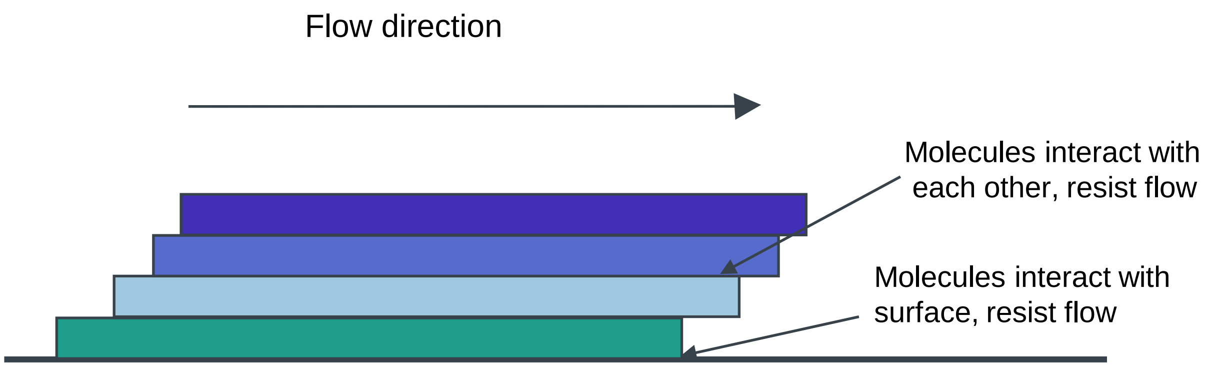
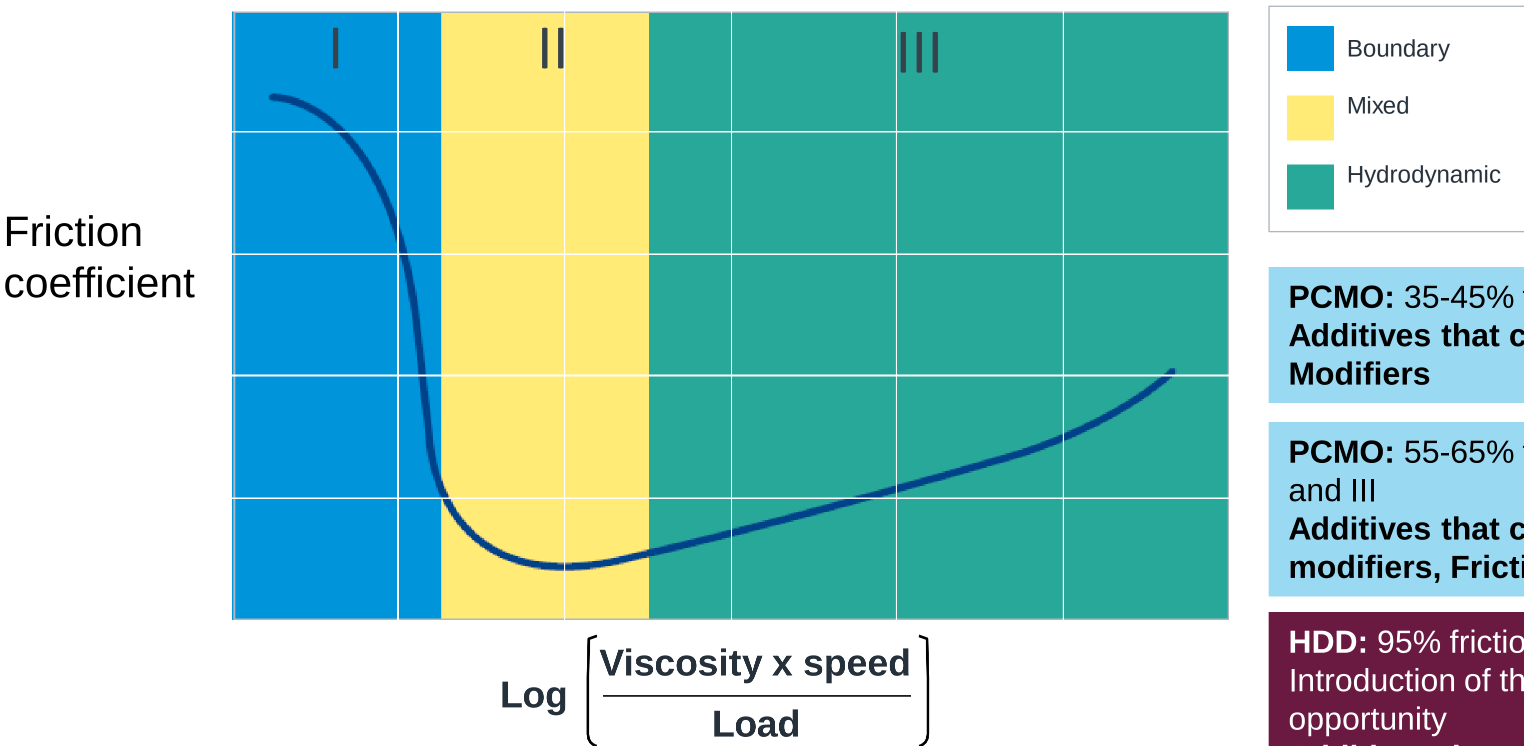
Molecular Origins of Viscosity

- Molecules in adjacent layers of oil interact, preventing layers from sliding past each other
- The higher the interaction the higher the resistance to flow (viscosity)
- Interacting Forces:



Stribeck Curve



PCMO: 35-45% frictional losses in I
Additives that can help: Friction Modifiers

PCMO: 55-65% frictional losses in II and III
Additives that can help: Viscosity modifiers, Friction Modifiers

HDD: 95% frictional losses in III
Introduction of thinner fluids is a big opportunity
Additives that can help: Viscosity modifiers

Viscosity index improvers and friction modifiers can be used in a complementary fashion in properly formulated engine oils to reduce friction because they operate in different lubrication regimes, as noted in the Stribeck Curve.

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Viscosity of Materials

Substance	Viscosity at room temp (mPa-s or cP)
Ketchup	100,000
VM Concentrate	40,000
Molasses	8,000
Maple syrup	3,000
Motor oil (SAE 8 – SAE 40 grades)	25 - 350
Olive oil	80
Group III base oil 4 cSt	45
Mercury	2
Water	1
Gasoline	0.5
Acetone	0.3
Air	0.018

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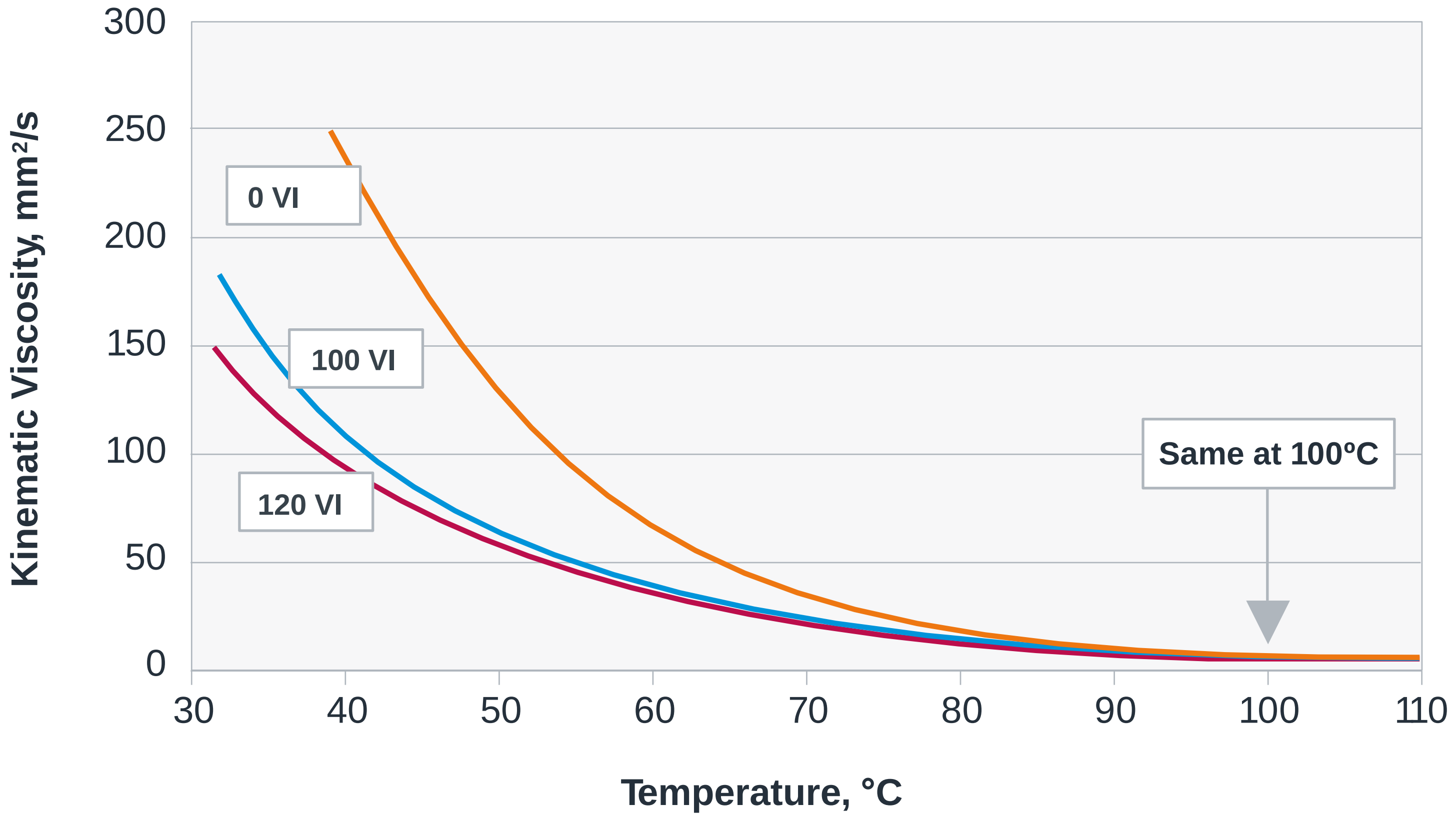
Viscosity Index



Viscosity Index (VI) defines the viscosity relationship with temperature.

- The Viscosity of low VI oils change significantly with temperature
- The Viscosity of high VI oils changes much less with temperature

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Viscosity Modifiers

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Viscosity Modifiers

- Viscosity Modifiers (VM) are used to reduce the influence of temperature on the viscosity of lubricants
  - Also known as Viscosity Index Improvers (VII)

- VMs used in crankcase lubricants are polymers

- VMs are used in the majority of engine oils and many transmission oils

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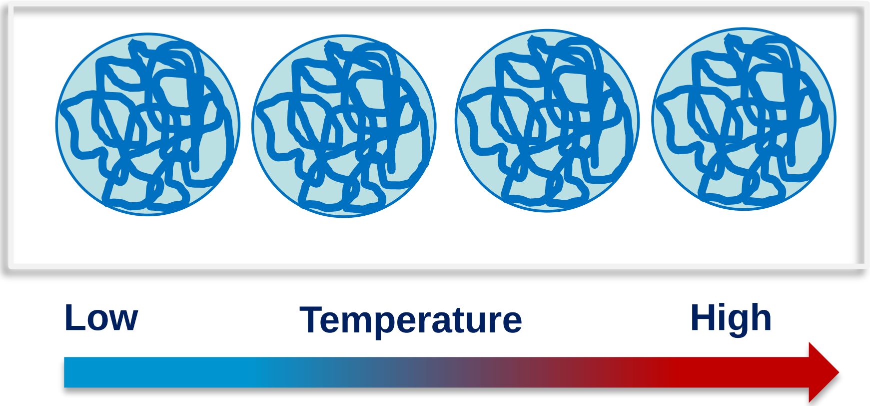
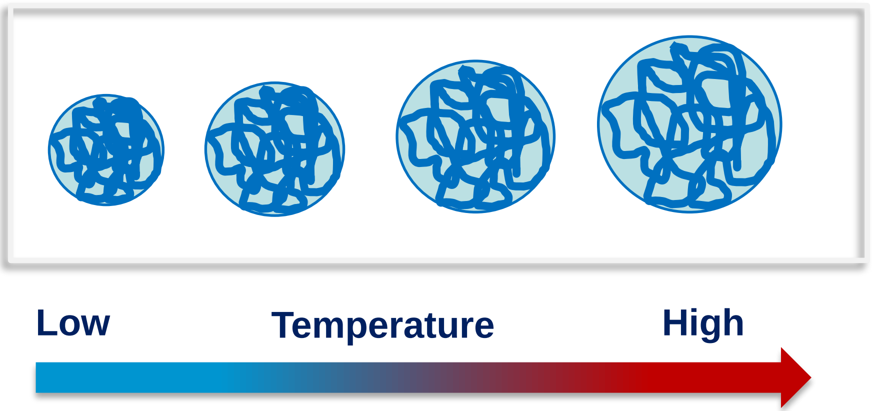
Viscosity Modifiers

- Polymeric Viscosity Modifiers occupy large volumes in solution
- Viscosity Modifiers increase viscosity proportionally to the volume that the polymer occupies
- The volume of the Viscosity Modifier in most cases is almost independent of temperature – there are some specific exceptions

OCPs, Hydrogenated Styrene dienes (HSD)



PMAs, temperature sensitive HSDs



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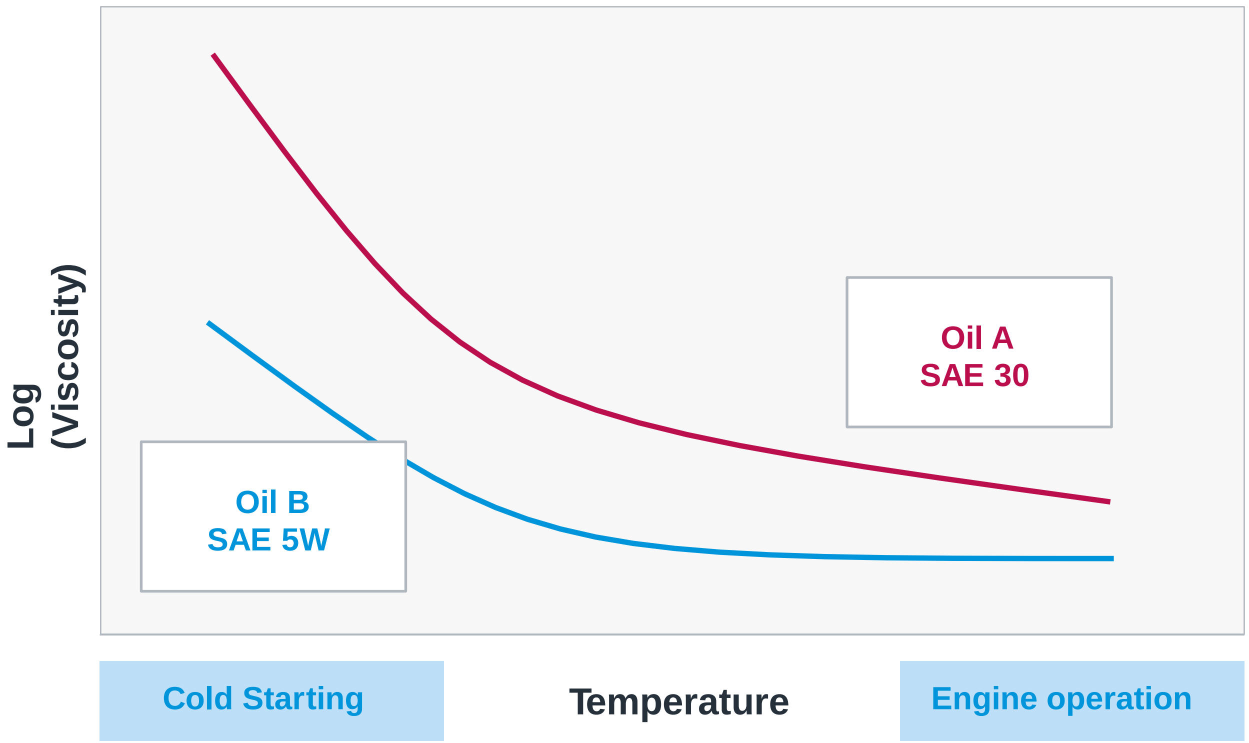
Function of viscosity modifiers

Function of Viscosity Modifiers



- Base oil viscosity has strong temperature dependence
- First described in 1920's and now more precisely in ASTM D341
- Thinner base oils (Oil B) provide good low temperature properties, but cannot provide protection at high temperatures
- Thicker base oils (Oil A) provide protection at high temperatures, but have insufficient pumpability at low temperatures

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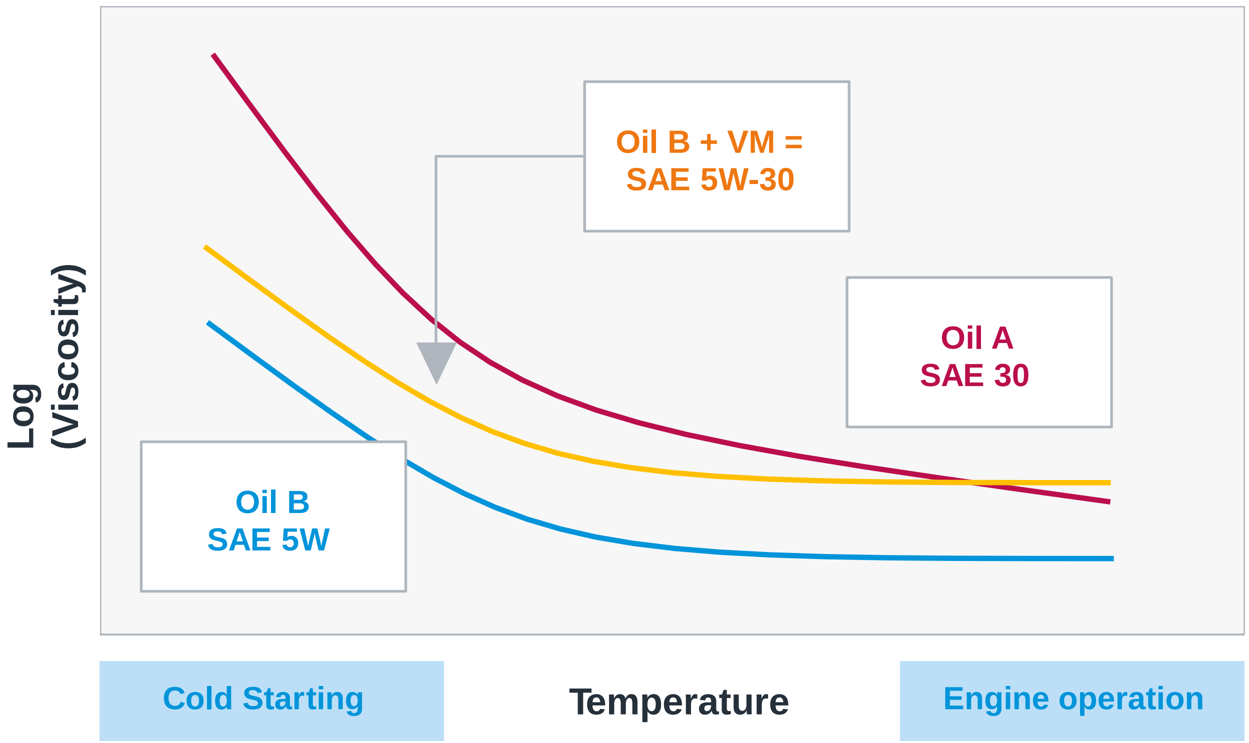
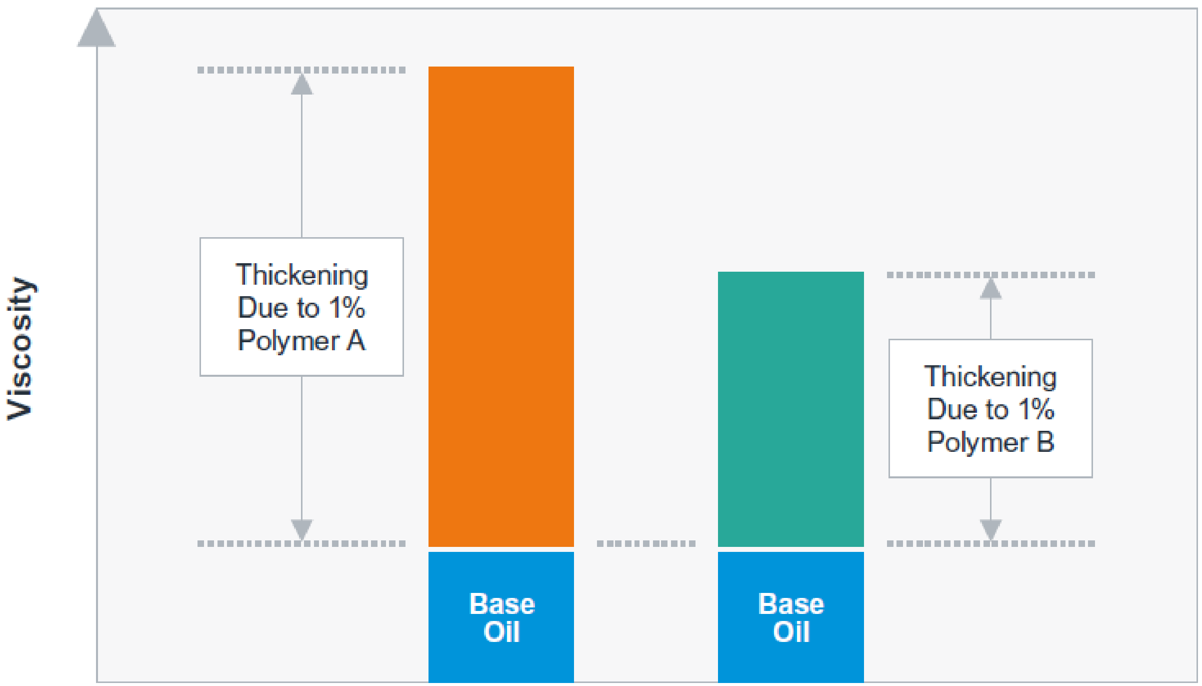
Function of Viscosity Modifiers



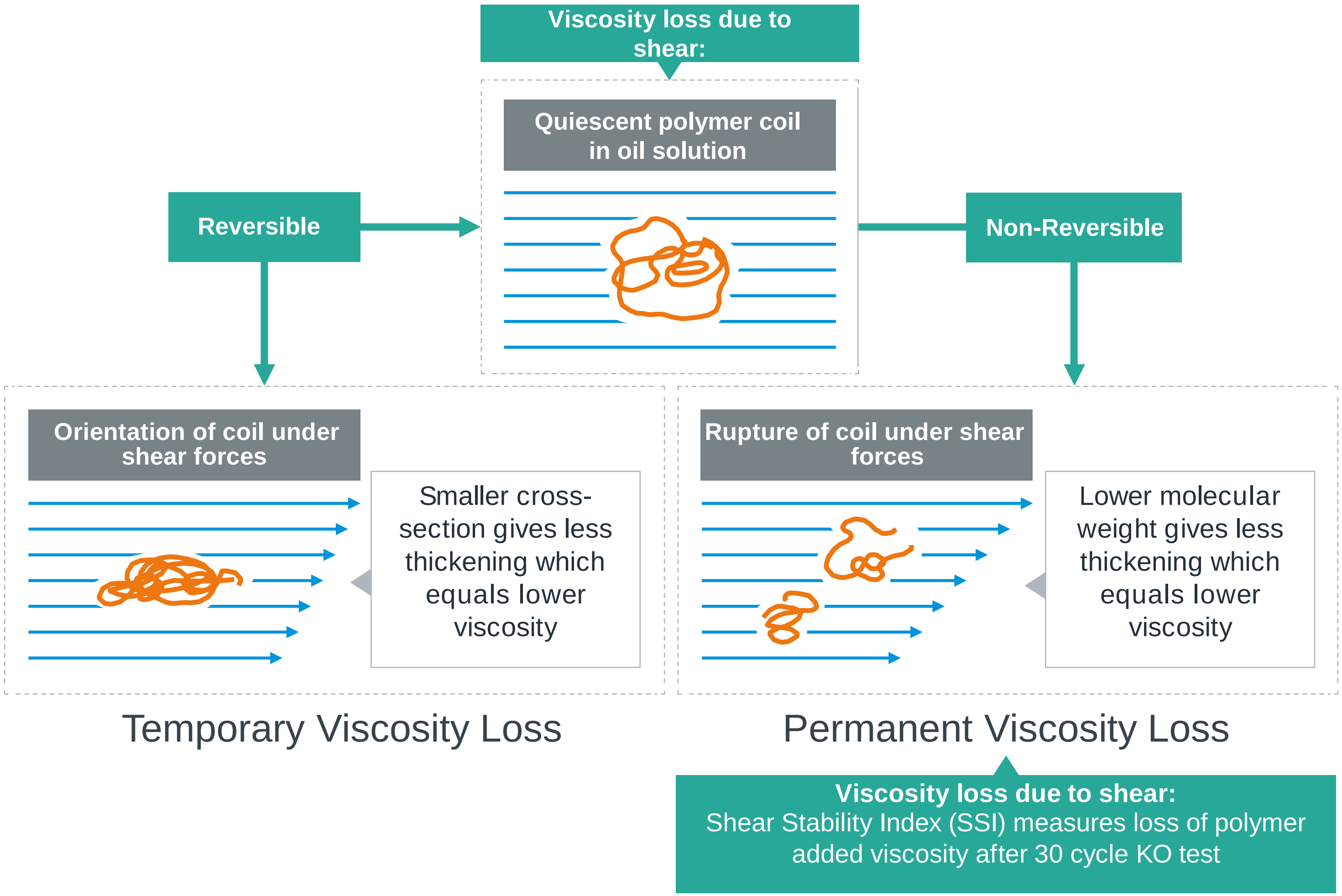
- VM adds viscosity to thinner oil at both high and low temperatures proportionally to base oil viscosity at the particular temperature
- VM added viscosity does not have strong dependence on temperature
- Reduces final oil temperature dependence
- Multigrade oils (SAE xW-xx) provide engine protection at both high and low temperatures through use of viscosity modifiers

Thickening Efficiency



- Thickening Efficiency or TE is the amount of viscosity increase per % polymer
- TE is highly dependent on Molecular Weight and chemistry
  - Higher MW = Higher TE
  - Less Branching = Higher TE
  - Better match of VM polarity to base oil polarity = Higher TE

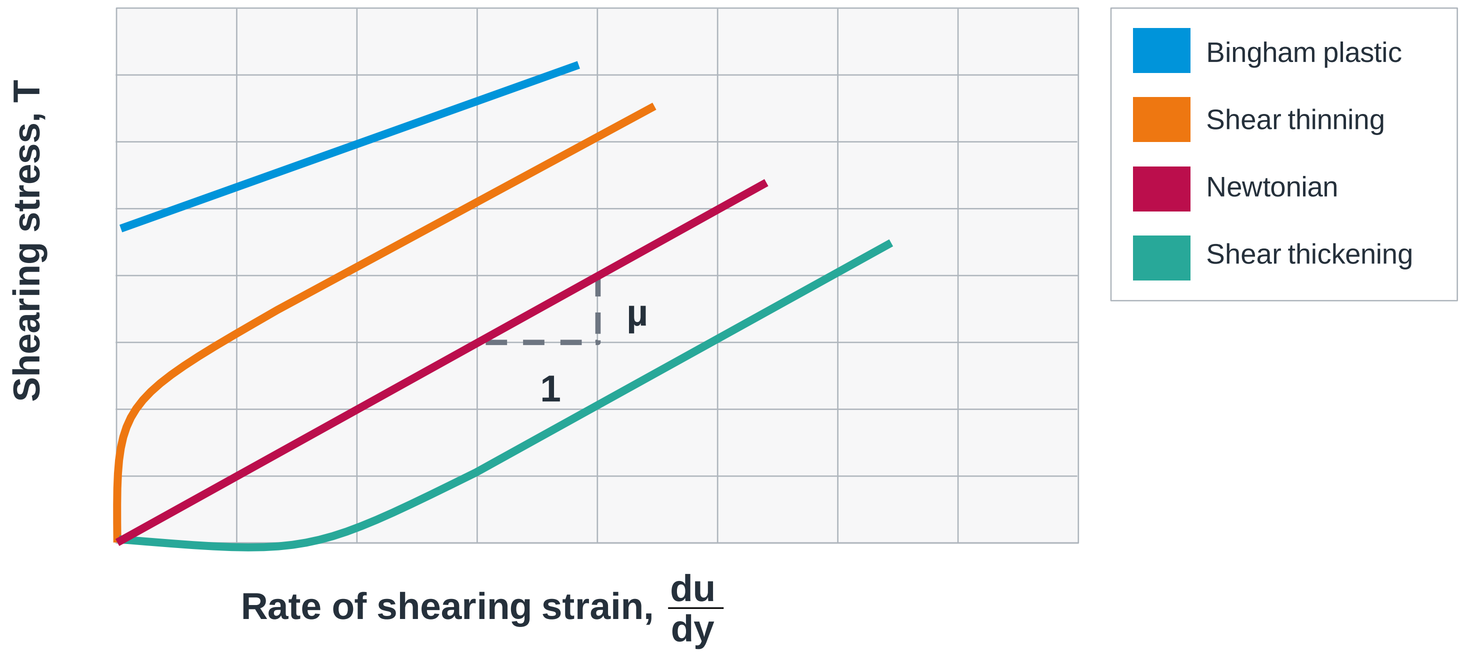
Shear-thinning: Temporary & Permanent Viscosity Loss



Shear Stability Index (permanent viscosity loss)

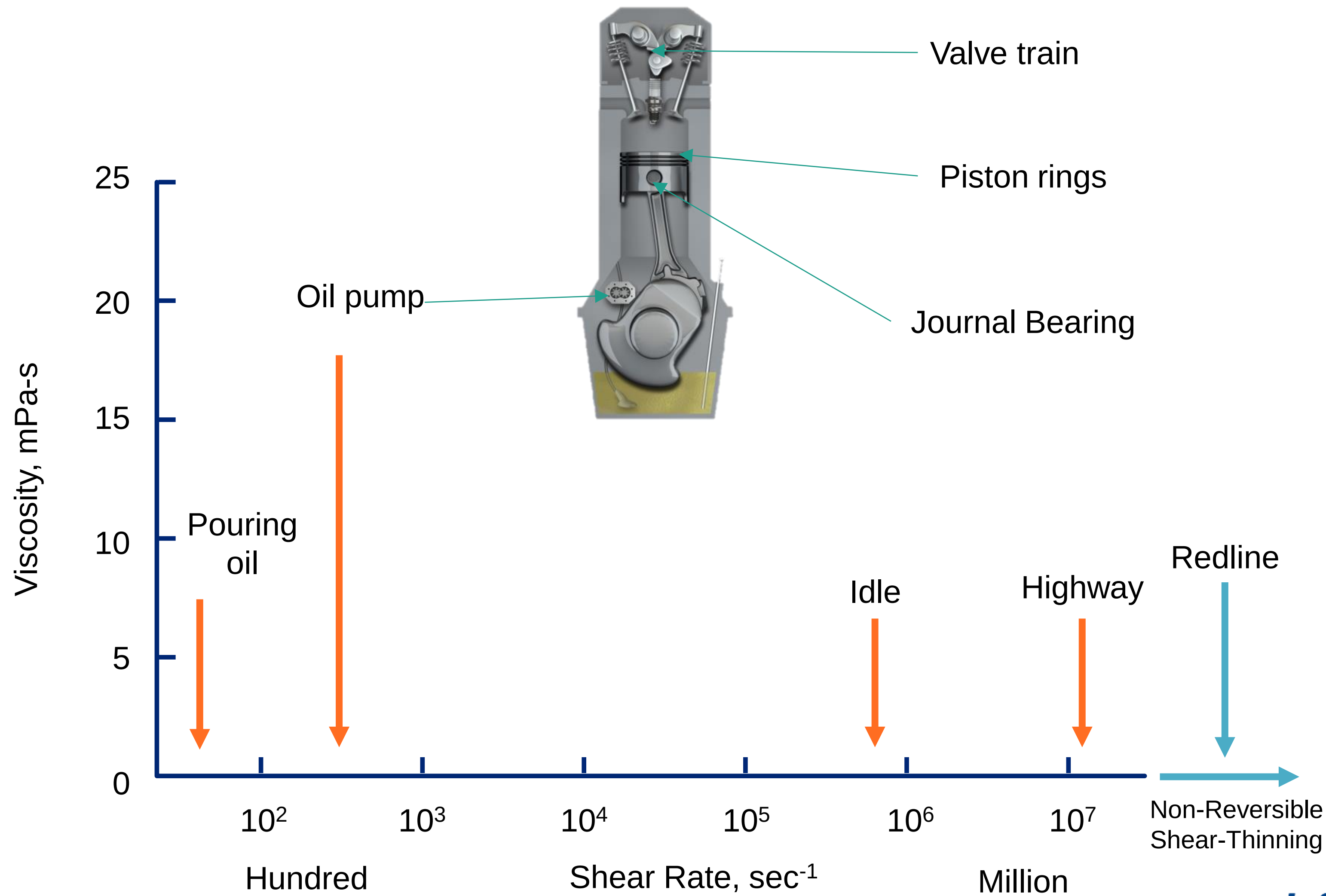
- Shear Stability Index (SSI) measures loss of polymer added kinematic viscosity after 30 cycles in Kurt Orbahn shear test
- The higher the SSI the more viscosity loss upon oil shearing
- SSI is usually measured in a reference oil that represents polymer behavior in SAE 15W-40 grade
- SSI depends on polymer chemistry, molecular geometry and molecular weight
  - Higher MW = less shear stable VM

Newton's law & shear thinning (temporary viscosity loss)



- Newton's Law of Viscosity: viscosity = shear stress / shear rate
- Newtonian Fluids = viscosity is a constant; does not change with shear stress or shear rate
- Fluids that do not obey this law are called Non-Newtonian
- The most common type is Shear-Thinning
  - Viscosity decreases with increasing shear rate
  - Viscosity modified fluids fall into this category

Typical Shear Rates



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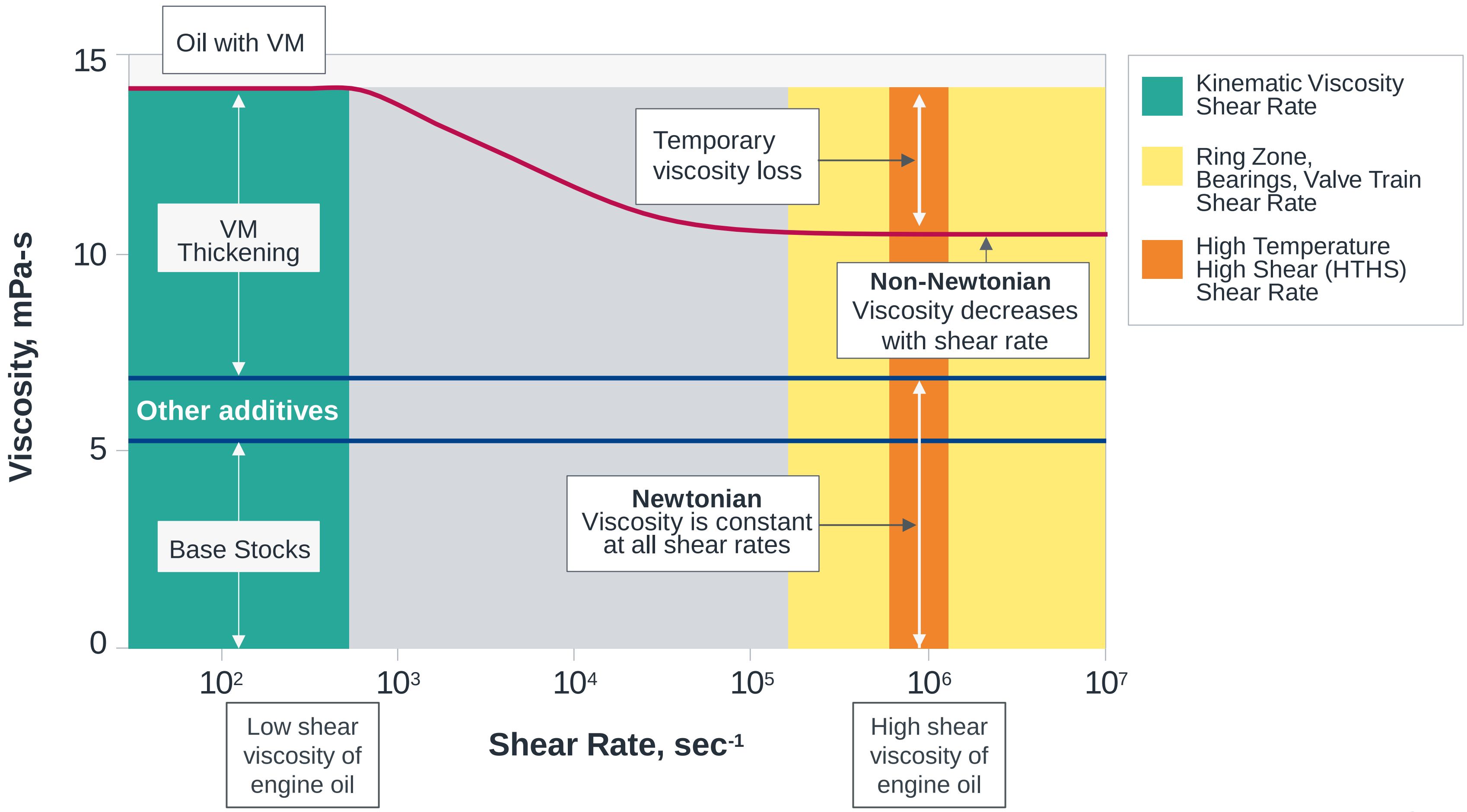
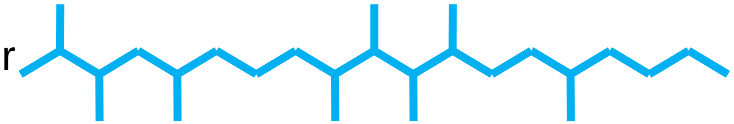
Shear rate & shear-thinning



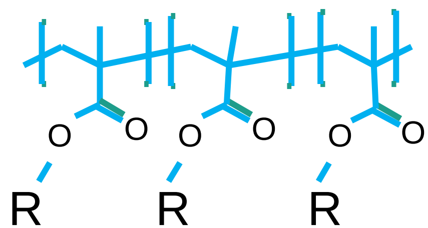
Viscosity Modifier Chemistry

Ethylene-Propylene Co-polymer (OCP)

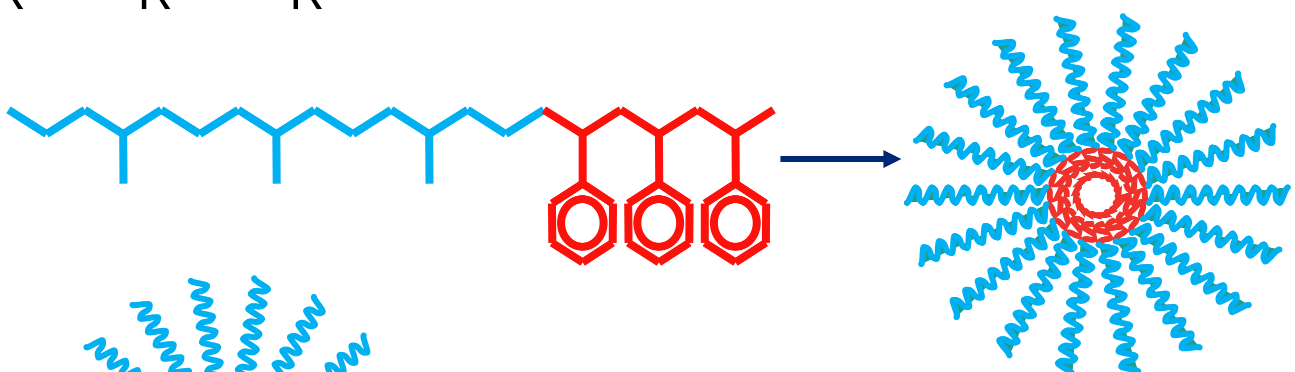


Can be semi-crystalline or amorphous depending on structural details

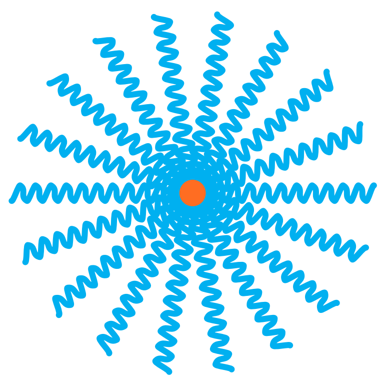
Polymethacrylate: (PMA)



Hydrogenated Styrene-Diene: Linear Polymer



Hydrogenated Styrene-Diene: Star Polymer



Chemically bonded together

Loose physical association due to polarity differences

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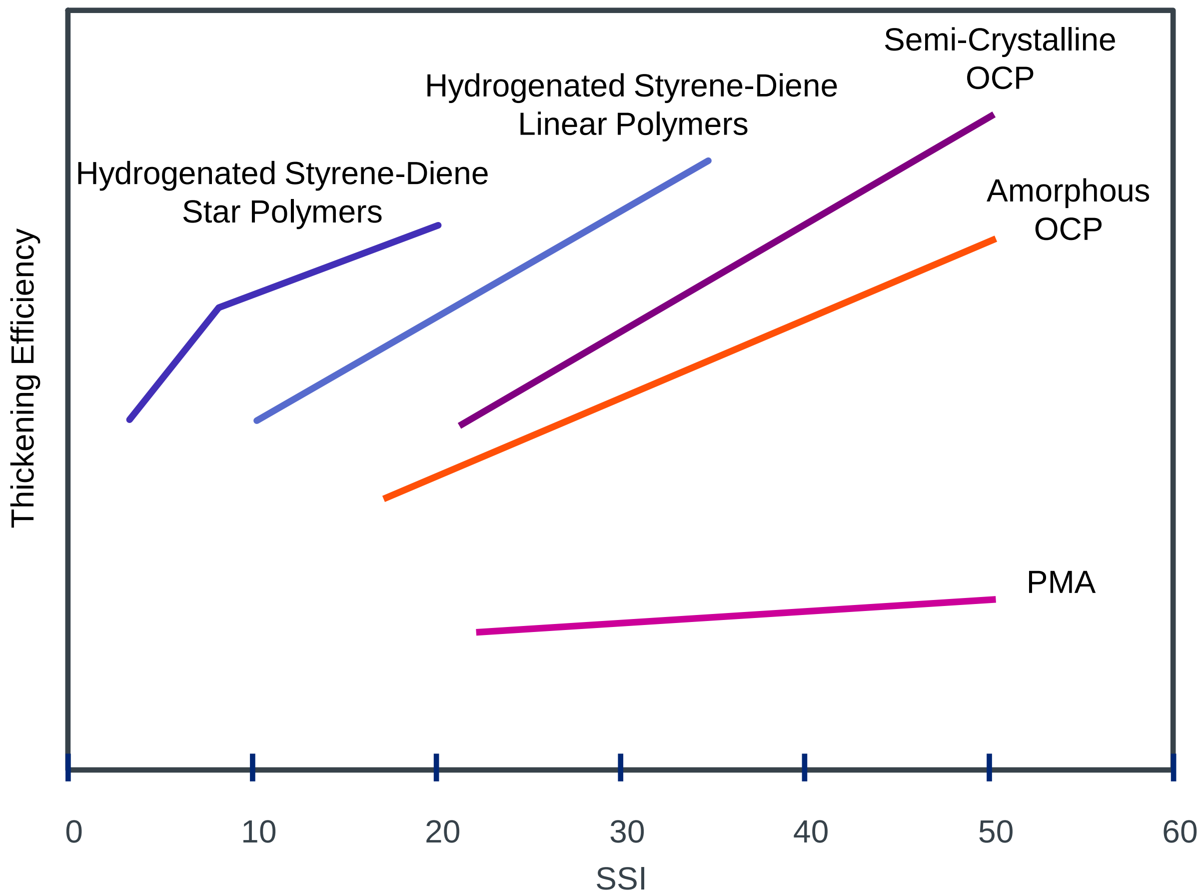
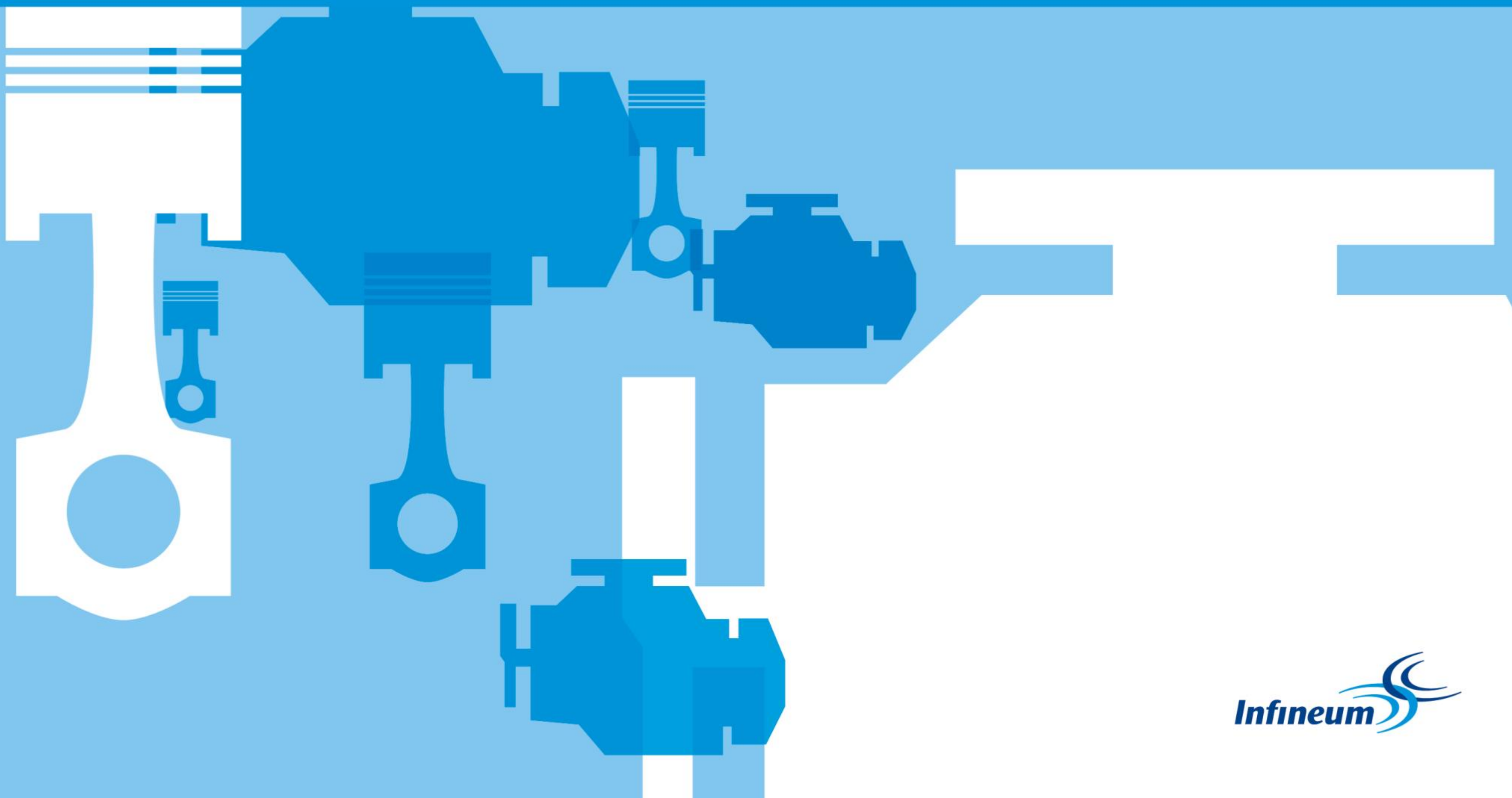
Performance comparison TE VS. SSI



Factors that need to be considered when selecting VM:

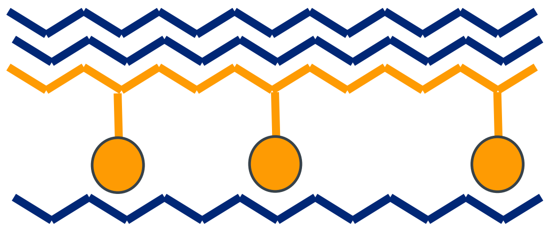
- Cost to achieve required thickening (Cost vs. TE)
- Shear Thinning Properties
- Low Temperature Properties
- Other performance harms/credits

Pour point depressants



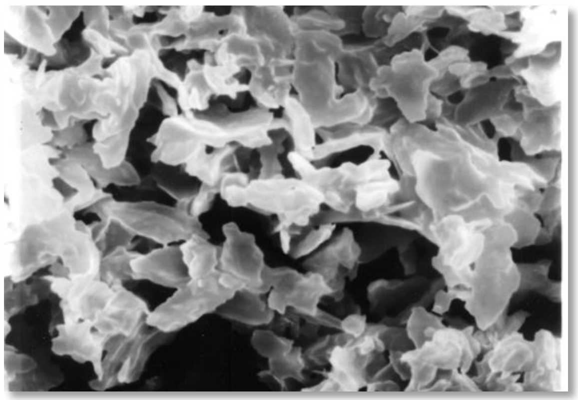
Pour Point Depressants

- Pour Point Depressants
  - Commonly referred to as PPDs
  - Also know as Lube Oil Flow Improvers (LOFIs)
- Break up the regularity of wax crystals
  - Prevent large crystal sheets from forming
  - Encourage small crystals - easier flow
  - Minimize low-temperature viscosity and yield stress
- Types:
  - Fumarate Vinyl Acetates (FVA)
  - Polymethacrylates (PMA)

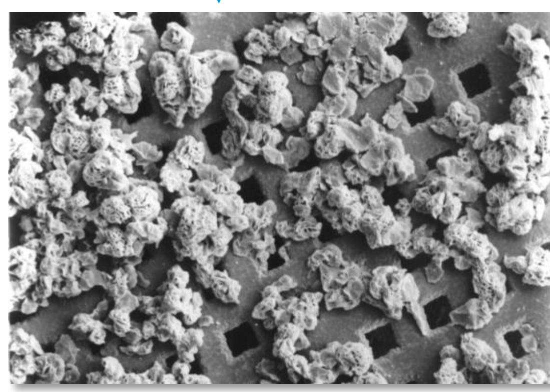


Wax crystal modification by PPD

- Wax crystals can cause the most serious type of engine problem
- Engines can start but the oil does not flow, leading to catastrophic engine failure



+ PPD



SAE viscosity grades

Viscosity measurement methods

Temp	Shear	Performance	Instrument	ASTM Method
High	Low	Oil Consumption Quality Control	Kinematic Viscometer	D 445
Low	High	Cold Starting	Cold Cranking Simulator (CCS)	D 5293
Low	Low	Cold Pumping	Mini-Rotary Viscometer (MRV)	D 4684
High	High	Wear/Fuel Economy	Tapered Bearing Simulator (TBS) Tapered Plug Viscometer (TPV) Multi-Cell Capillary (MCC)	D 4683 D 4741 D 5481

SAE J300 Engine Oil Viscosity Grades (issued January 2015)

SAE Grade	CCS mPa-s, Max	MRV mPa-s, Max w/No Yield Stress	Kinematic Viscosity mm^2/s Min	Kinematic Viscosity mm^2/s Max	HTHS @ 10^6 Sec^{-1} mPa-s, Min
0W	6200 at -35°C	60 000 at -40°C	3.8	–	–
5W	6600 at -30°C	60 000 at -35°C	3.8	–	–
10W	7000 at -25°C	60 000 at -30°C	4.1	–	–
15W	7000 at -20°C	60 000 at -25°C	5.6	–	–
20W	9500 at -15°C	60 000 at -20°C	5.6	–	–
25W	13000 at -10°C	60 000 at -15°C	9.3	–	–
8	–	–	**4.0**	**<6.1**	**1.7**
12	–	–	**5.0**	**<7.1**	**2.0**
16	–	–	**6.1**	**<8.2**	**2.3**
20	–	–	**6.9**	<9.3	2.6
30	–	–	9.3	<12.5	2.9
40	–	–	12.5	<16.3	3.5(1)
40	–	–	12.5	<16.3	3.7(2)
50	–	–	16.3	<21.9	3.7
60	–	–	21.9	<26.1	3.7

(1) For 0W, 5W, 10W Multigrades – Changed from 2.9 in 11/2007

(2) For 15W, 20W, 25W Multigrades and SAE 40 Grade

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SAE viscosity grades

'Summer' Grade						
60	0W-60	5W-60	10W-60	15W-60	20W-60	25W-60
50	0W-50	5W-50	10W-50	15W-50	20W-50	25W-50
40	0W-40	5W-40	10W-40	15W-40	20W-40	25W-40
30	0W-30	5W-30	10W-30	15W-30	20W-30	25W-30
20	0W-20	5W-20	10W-20	15W-20	20W-20	
16	0W-16	5W-16				
12	0W-12					
8	0W-8					
	0W	5W	10W	15W	20W	25W

'Winter' Grade

Straight Grades

Some common viscosity grades for engine oils

•SAE 0W-X grades typically need synthetic base stocks

SAE J300 Engine oil viscosity grades

- Correct
  - SAE 10W-30
- Incorrect
  - 10W-30
  - SAE 10W/30
  - SAE 10W30
  - SAE 10w-30
- Labeling
  - Must label as the lowest ‘W’ grade
    - An oil that meets 5W also meets 10W, 15W, etc.
  - Oils with VM must be labeled as Multigrades
- Need to take care with CCS and HTHS labelling as there is overlap between the SAE grades

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Summary

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Summary

- Viscosity is a measure of a fluid's resistance to flow
  - It depends strongly on temperature
  - Can depend on shear rate
- Viscosity modifiers in lubricants:
  - Used to reduce the influence of temperature on lubricant viscosity
  - Chemical structure and molecular weight affect performance and efficiencies
  - Exhibit temporary and permanent viscosity loss due to shear
  - Three common types: OCPs, Hydrogenated Styrene-diene Co-polymer, PMAs
  - Oil formulators must balance viscometric requirements, engine performance and cost
- Viscosity grades are defined by SAE J300
  - *"Oils which are formulated with polymeric viscosity index improvers for the purpose of making them multiviscosity-grade products are non-Newtonian and must be labelled with the appropriate multiviscosity grade". Source: SAE J300*

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Appendix: viscosity measurement methods

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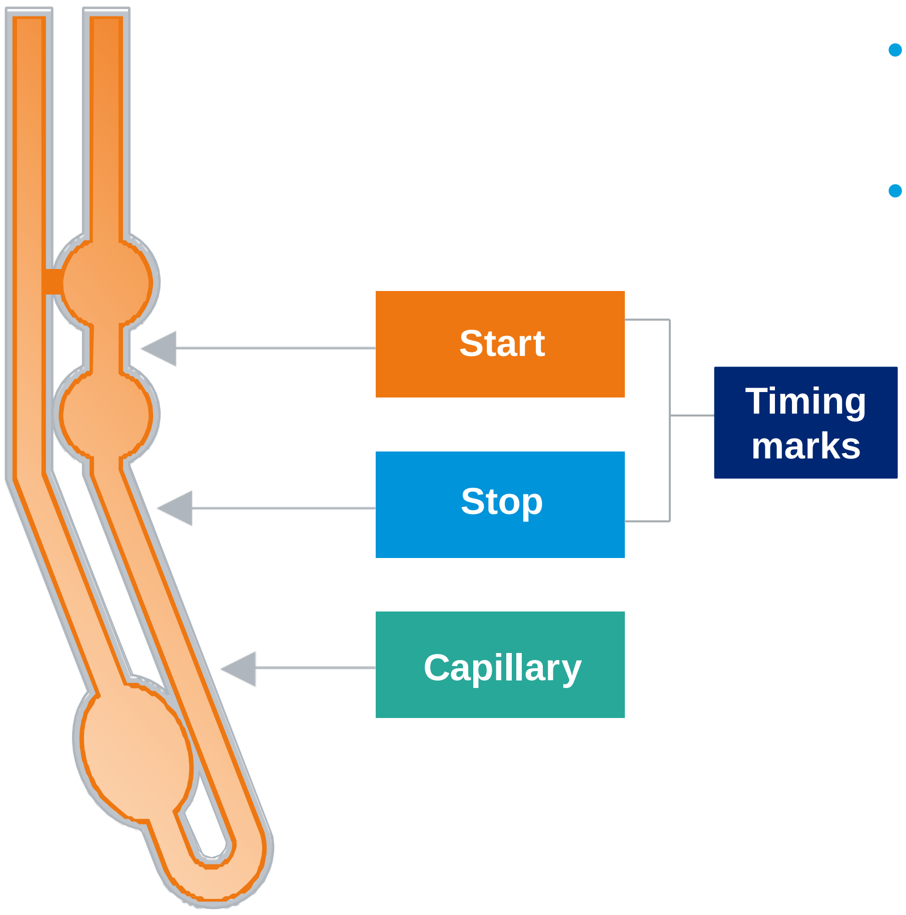
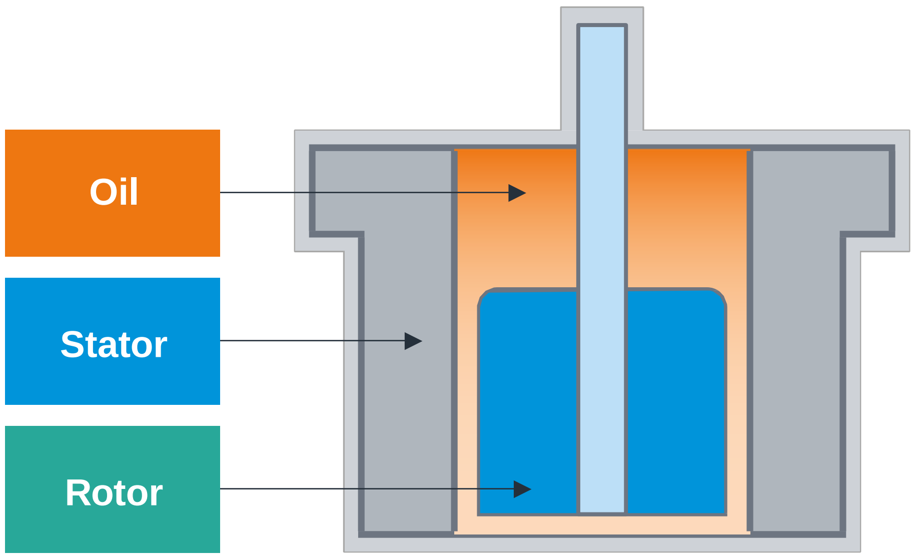
Kinematic viscosity



- Kinematic viscosity = viscosity/density
- Principle
  - Measure time for known volume to flow through capillary tube
    - Driving force: gravity (mass of fluid)
    - Low shear rate
  - Units
    - mm2/s
    - CentiStokes = cSt (discouraged)
    - Saybolt Universal Seconds (SUS) (obsolete)

Cold cranking simulator



-500 to 200,000 mPa-s

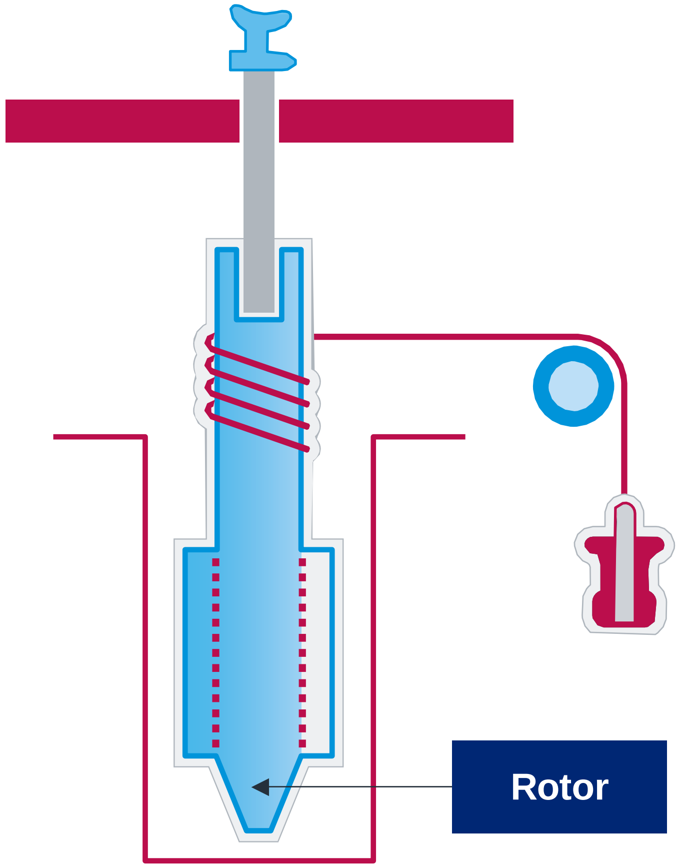
-10^4 to 10^6 sec^{-1}

-50,000 Pa

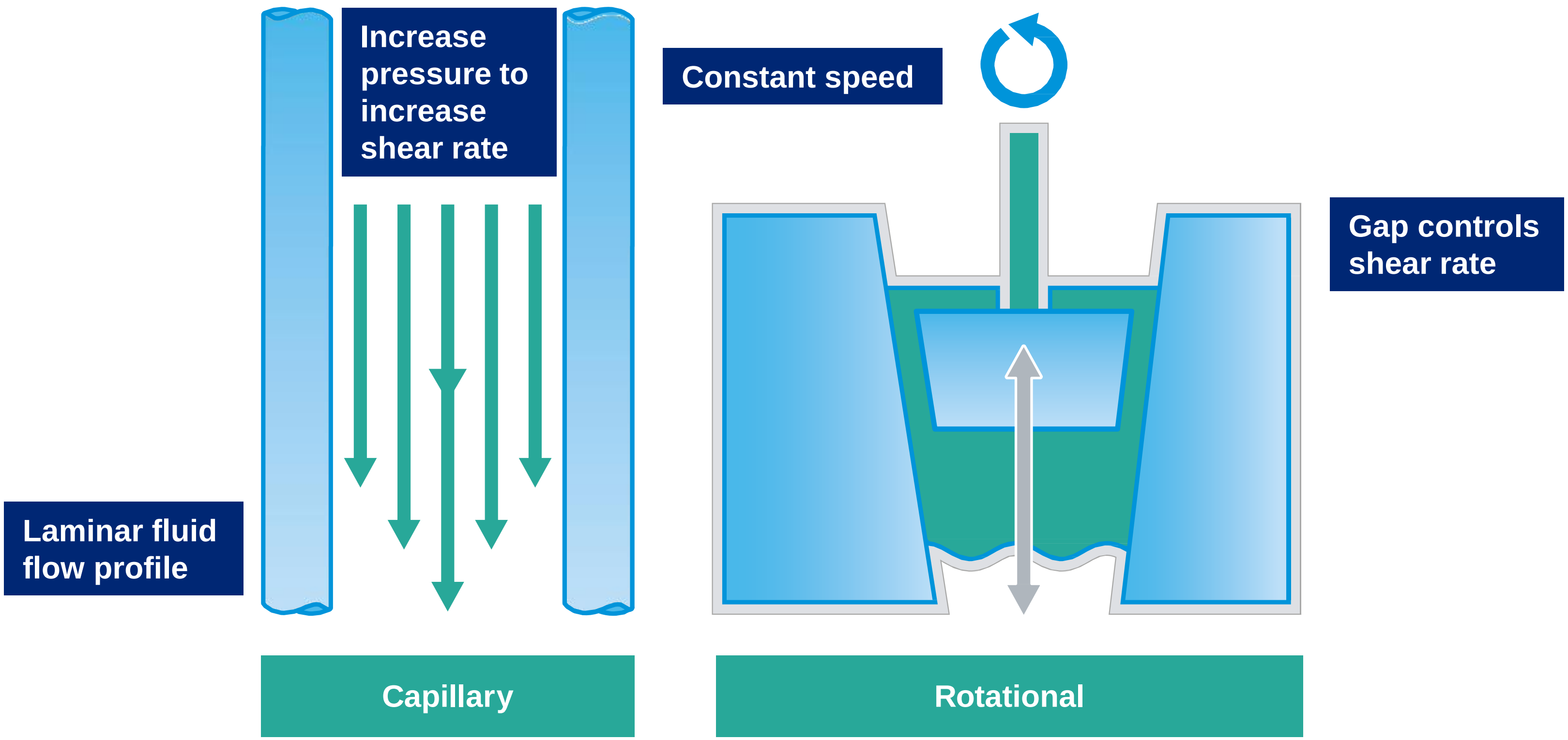
CCS cross-section

Mini-rotary viscometer

- Low shear rate/shear stress measurement
- Measurements
  - Yield stress
    (min. stress to cause flow)
  - Viscosity @ 525 Pa stress)
- Relationship to pumpability failure mechanism
  - Yield stress/air-binding
  - Viscosity/flow-limited



High temperature high shear



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