Densities and Viscosities of MTBE + Nonane or Decane at $p = 0.1$ MPa from (273.15 to 363.15) K

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This work presents densities and viscosities at atmospheric conditions for methyl *tert*-butyl ether (MTBE) + nonane, or decane, over the whole range of compositions from (273.15 to 363.15) K. A vibrating tube densimeter has been used for the density measurements and a Cannon-Fenske viscosimeter for the viscosity measurements. Excess molar volumes have been calculated from the density measurements and have been represented with a Redlich–Kister equation. The average absolute deviation of our excess molar volumes from literature values is within 0.015 $cm^3 \cdot mol^{-1}$. We also have represented our kinematic viscosity values with a three-body McAllister equation.

Introduction

This work is a continuation of a previous paper[1] that presents the densities and viscosities of methyl *tert*-butyl ether (MTBE) with heptane and with octane over the whole composition range. Here, the densities of MTBE + nonane and + decane have been measured with a vibrating densimeter from (273.15 to 363.15) K over the entire composition range. Also, the kinematic viscosities of these mixtures have been measured using a Cannon-Fenske viscosimeter from (273.15 to 333.15) K over the whole composition range. Excess molar volumes are calculated using Redlich–Kister-type equations.[2] Constants for a three-body McAllister equation[3] have been reported to calculate the kinematic viscosity of these mixtures. Also, dynamic viscosity values were generated from our kinematic viscosity results and the density measurements.

Experimental

Apparatus and Procedures. Our vibrating tube densimeter (Anton Paar, model DMA 5000) was described earlier.[4] The reproducibility in the density and temperature measurements provided by the manufacturer are ± 0.001 $kg \cdot m^{-3}$ and ± 0.001 K, respectively. The uncertainties of the thermometer and the density measurements are ± 0.01 K on ITS-90 and ± $5 \cdot 10^{-6}$ $g \cdot cm^{-3}$, respectively. The true uncertainty in the density measurements is probably better than ± $3 \cdot 10^{-5}$ $g \cdot cm^{-3}$. As stated before,[1] the uncertainty in the excess volume is 0.008 $cm^3 \cdot mol^{-1}$.

The kinematic viscosity is measured using a Cannon-Fenske viscosimeter (size 25) with flow ranges of (0.5 to 2)$\cdot 10^{-6}$ $m^2 \cdot s^{-1}$. Measurements are performed according to the ASTM 445 standard. The viscosimeter resides in a Polyscience constant-temperature water bath controlled within ± 0.01 K. A digital thermometer measures the temperature with an accuracy of 0.01 K. The efflux time is measured manually using a digital stopwatch having an accuracy of 0.01 s. Each datum is an average of at least five runs with a maximum deviation in the kinematic viscosity of ± 0.1 %, and the estimated accuracy[1] of each measurement is better than ± 0.004 $mPa \cdot s$.

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Table 1. Comparison between Experimental Densities and Literature Values for Nonane and Decane

	$\rho/g \cdot cm^{-3}$		$\rho/g \cdot cm^{-3}$	
T/K	this work	lit.	this work	lit.
	Nonane		Decane	
273.15	0.733184	0.733[7]	0.745374	
278.15	0.729335		0.741257	
283.15	0.725473	0.72539[8]	0.737502	0.73738[8]
288.15	0.721603		0.733733	0.73338[17]
293.15	0.717725	0.71775[9]	0.729958	0.72995[18]
298.15	0.713834	0.7138[8]	0.726174	0.72609[19]
		0.71385[10]		
303.15	0.709929	0.70992[11]	0.722377	0.72229[12]
308.15	0.706011	0.7061[12]	0.718573	0.7186[20]
313.15	0.702076	0.70235[13]	0.714753	0.71469[21]
318.15	0.698124	0.69807[14]	0.710920	
323.15	0.694151	0.6939[14]	0.707074	0.70687[14]
				0.708[22]
328.15	0.690165	0.69024[14]	0.703213	0.703708[14]
333.15	0.686154	0.6864[15]	0.699334	0.69924[14]
338.15	0.682116	0.68202[14]	0.695439	0.69559[14]
343.15	0.678060	0.677884[16]	0.691522	0.69148[14]
348.15	0.673979	0.673908[16]	0.687587	0.68759[23]
353.15	0.669872	0.669706[16]	0.683631	0.68354[14]
358.15	0.665730	0.66561[14]	0.679651	0.67943[14]
363.15	0.661557		0.675648	0.67559[14]

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Table 2. Experimental Densities and Excess Molar Volumes for MBTE (1) + Nonane (2)

x_1	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$
	T = 273.15 K		T = 278.15 K		T = 283.15 K		T = 288.15 K		T = 293.15 K	
0.0000		0		0		0		0		0
0.1085	0.73469	0.1355	0.73078	0.1301	0.72684	0.127	0.72290	0.1229	0.71892	0.1260
0.1722	0.73567	0.2064	0.73171	0.1987	0.72773	0.194	0.72373	0.1894	0.71972	0.1851
0.3037	0.73789	0.3404	0.73382	0.3283	0.72973	0.3215	0.72562	0.3150	0.72151	0.3073
0.4011	0.73994	0.3856	0.73578	0.3719	0.73159	0.365	0.72739	0.3575	0.72316	0.3499
0.5008	0.74231	0.4125	0.73804	0.3964	0.73374	0.3897	0.72943	0.3818	0.72509	0.3737
0.6005	0.74508	0.4014	0.74068	0.3843	0.73626	0.3784	0.73181	0.3711	0.72734	0.3635
0.6992	0.74817	0.3709	0.74364	0.3531	0.73908	0.3474	0.73449	0.3409	0.72987	0.3345
0.8005	0.75189	0.2963	0.74720	0.2779	0.74247	0.2741	0.73772	0.2685	0.73294	0.2628
0.8925	0.75581	0.1924	0.75095	0.1743	0.74606	0.1719	0.74113	0.1687	0.73617	0.1645
1.0000	0.76134	0	0.75614	0	0.75102	0	0.74585	0	0.74065	0
	T = 298.15 K		T = 303.15 K		T = 308.15 K		T = 313.15 K		T = 318.15 K	
0.0000		0		0		0		0		0
0.1085	0.71495	0.1229	0.71096	0.1184	0.70697	0.1124	0.70296	0.1070	0.69889	0.1084
0.1722	0.71570	0.1803	0.71166	0.1749	0.70760	0.1710	0.70352	0.1659	0.69942	0.1594
0.3037	0.71736	0.3002	0.71321	0.2902	0.70903	0.2845	0.70482	0.2757	0.70060	0.2638
0.4011	0.71892	0.3400	0.71465	0.3313	0.71036	0.3259	0.70605	0.3151	0.70171	0.3031
0.5008	0.72073	0.3647	0.71634	0.3543	0.71193	0.3484	0.70749	0.3373	0.70301	0.3255
0.6005	0.72284	0.3561	0.71832	0.3466	0.71377	0.3420	0.70918	0.3321	0.70456	0.3200
0.6992	0.72522	0.3272	0.72055	0.3177	0.71584	0.3163	0.71109	0.3079	0.70630	0.2976
0.8005	0.72811	0.2572	0.72325	0.2509	0.71835	0.2533	0.71341	0.2473	0.70845	0.2346
0.8925	0.73118	0.1600	0.72613	0.1566	0.72104	0.1613	0.71591	0.1577	0.71072	0.1531
1.0000	0.73540	0	0.73010	0	0.72482	0	0.71942	0	0.71396	0
	T = 323.15 K		T = 328.15 K		T = 333.15 K		T = 338.15 K		T = 343.15 K	
0.0000										
0.1085	0.69483		0.69074		0.68664		0.68252		0.67837	
0.1722	0.69530		0.69116		0.68699		0.68279		0.67857	
0.3037	0.69634		0.69206		0.68776		0.68342		0.67905	
0.4011	0.69734		0.69294		0.68850		0.68402		0.67952	
0.5008	0.69851		0.69397		0.68939		0.68476		0.68011	
0.6005	0.69989		0.69519		0.69045		0.68566		0.68083	
0.6992	0.70146		0.69659		0.69166		0.68668			
0.8005	0.70335		0.69827		0.69314		0.68795			
0.8925	0.70548									
1.0000										
	T = 348.15 K		T = 353.15 K		T = 358.15 K		T = 363.16 K			
0.0000										
0.1085	0.67419		0.66995		0.66571		0.66143			
0.1722	0.67431		0.67002		0.66570		0.66133			
0.3037	0.67464		0.67019		0.66570		0.66117			
0.4011	0.67498		0.67038		0.66575					
0.5008										
0.6005										
0.6992										
0.8005										
0.8925										
1.0000										

Chemicals. Sigma Aldrich Co. supplied the MBTE, nonane, and decane with stated molar fraction purities of better than 99.8 %, 99 %, and 99 %, respectively. The confirmed purities of the samples from the manufacturer (certificates of analysis) are 99.96 %, 99.44 %, and 99.6 % for MBTE, nonane, and decane, respectively. The pure components are used as received. The mixtures were prepared gravimetrically using an analytical balance (Ohaus Model AS120S) with a precision of ± 0.1 mg. The overall uncertainty in the mole fractions is better than ± 0.002.

Results and Discussion

The density and viscosity of the pure components are measured to check the purities of the samples. Table 1 presents the comparison of the density measurements to literature values. Our values agree within an average absolute percentage deviation of 0.02 % and 0.03 % for nonane and decane, respectively. Also, the liquid density of mixtures of MBTE + nonane and + decane have been measured from (273.15 to 363.15) K. For MTBE + nonane, our density values agree with measurements from Rodríguez et al.[5] within an average absolute percentage deviation of 0.02 %. Tables 2 and 3 contain our density measurements for MTBE + nonane and + decane, respectively. Pure MTBE densities are reported before,[1] but they are included here for completeness.

The excess molar volumes have been calculated as reported earlier.[1] Excess molar volumes of MBTE with nonane and with decane have positive deviations from ideality at the

Table 3. Experimental Densities and Excess Molar Volumes for MBTE (1) + Decane (2)

x_1	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$	ρ / $g\cdot cm^{-3}$	V^E / $cm^3\cdot mol^{-1}$
	T = 273.15 K		T = 278.15 K		T = 283.15 K		T = 288.15 K		T = 293.15 K	
0		0		0		0		0		0
0.1019	0.74552	0.2179	0.74170	0.1274	0.73788	0.1249	0.73404	0.1204	0.73020	0.1155
0.2041	0.74617	0.3191	0.74228	0.234	0.73838	0.228	0.73447	0.2191	0.73055	0.2094
0.3077	0.74706	0.3825	0.74309	0.3017	0.73910	0.2935	0.73510	0.2816	0.73109	0.2698
0.3999	0.74800	0.424	0.74394	0.35	0.73986	0.3399	0.73577	0.3268	0.73166	0.3138
0.5005	0.74923	0.4453	0.74506	0.378	0.74087	0.3663	0.73666	0.3528	0.73244	0.3386
0.6066	0.75084	0.4349	0.74653	0.3763	0.74220	0.3659	0.73784	0.3534	0.73347	0.3398
0.6866	0.75232	0.4006	0.74790	0.3484	0.74344	0.3386	0.73897	0.3261	0.73447	0.3133
0.7973	0.75483	0.312	0.75021	0.2709	0.74555	0.2639	0.74088	0.2544	0.73617	0.2442
0.8999	0.75782	0.1703	0.75299	0.1396	0.74812	0.1349	0.74323	0.1278	0.73830	0.121
1	0.76134	0	0.75614	0	0.75102	0	0.74585	0	0.74065	0
	T = 298.15 K		T = 303.15 K		T = 308.15 K		T = 313.15 K		T = 318.15 K	
0		0		0		0		0		0
0.1019	0.72635	0.1095	0.72246	0.1095	0.71859	0.1034	0.71470	0.096	0.71081	0.0841
0.2041	0.72662	0.1997	0.72268	0.1883	0.71872	0.1791	0.71474	0.167	0.71074	0.1541
0.3077	0.72706	0.2572	0.72302	0.2427	0.71896	0.2315	0.71488	0.2152	0.71078	0.1983
0.3999	0.72753	0.2999	0.72338	0.2842	0.71922	0.2725	0.71503	0.2547	0.71082	0.2352
0.5005	0.72819	0.3231	0.72393	0.3047	0.71962	0.2952	0.71530	0.2773	0.71097	0.2521
0.6066	0.72907	0.3251	0.72465	0.3081	0.72020	0.2972	0.71570	0.2832	0.71120	0.2603
0.6866	0.72994	0.2987	0.72539	0.2815	0.72081	0.2715	0.71618	0.2556	0.71153	0.2362
0.7973	0.73144	0.2321	0.72666	0.2197	0.72185	0.2168	0.71700	0.204	0.71210	0.1894
0.8999	0.73333	0.1131	0.72832	0.1052	0.72326	0.1072	0.71816	0.0989	0.71301	0.0898
1	0.73540	0	0.73010	0	0.72482	0	0.71942	0	0.71396	0
	T = 323.15 K		T = 328.15 K		T = 333.15 K		T = 338.15 K		T = 343.15 K	
0										
0.1019	0.70689		0.70296		0.69900		0.69502		0.69102	
0.2041	0.70673		0.70270		0.69864		0.69456		0.69046	
0.3077	0.70665		0.70251		0.69834		0.69414		0.68992	
0.3999	0.70659		0.70233		0.69805		0.69373		0.68938	
0.5005	0.70660		0.70222		0.69778		0.69331		0.68880	
0.6066	0.70667		0.70211		0.69750		0.69286		0.68818	
0.6866	0.70684		0.70211		0.69732		0.69258		0.68771	
0.7973	0.70718		0.70219		0.69715		0.69206		0.68692	
0.8999	0.70781		0.70255							
1										
	T = 348.15 K		T = 353.15 K		T = 358.15 K		T = 363.15 K			
0										
0.1019	0.68701		0.68296		0.67889		0.67479			
0.2041	0.68634		0.68218		0.67800		0.67378			
0.3077	0.68567		0.68138		0.67706		0.67271			
0.3999	0.68501		0.68059		0.67614		0.67166			
0.5005	0.68426		0.67969							
0.6066	0.68343		0.67865							
0.6866										
0.7973										
0.8999										
1										

Table 4. Parameters for the Redlich–Kister Equation for the Excess Molar Volume

T/K	a_0	a_1	a_2	$\sigma/cm^3\cdot mol^{-1}$
		MTBE + Nonane		
273.15	1.65	0.29	0.076	0.008
278.15	1.59	0.23	−0.004	0.007
283.15	1.56	0.24	−0.007	0.007
288.15	1.53	0.24	−0.017	0.007
293.15	1.5	0.23	0.006	0.006
298.15	1.46	0.23	0.006	0.006
303.15	1.42	0.23	0.004	0.005
308.15	1.4	0.27	0.039	0.006
313.15	1.36	0.27	0.045	0.006
318.15	1.3	0.26	0.058	0.005
		MTBE + Decane		
273.15	1.77	−0.04	0.532	0.014
278.15	1.52	0.21	0.016	0.007
283.15	1.47	0.2	0.026	0.008
288.15	1.42	0.19	0.013	0.008
293.15	1.37	0.18	−0.002	0.008
298.15	1.31	0.17	−0.025	0.009
303.15	1.23	0.15	−0.004	0.009
308.15	1.18	0.18	0.023	0.008
313.15	1.12	0.18	−0.004	0.009
318.15	1.03	0.17	−0.012	0.008

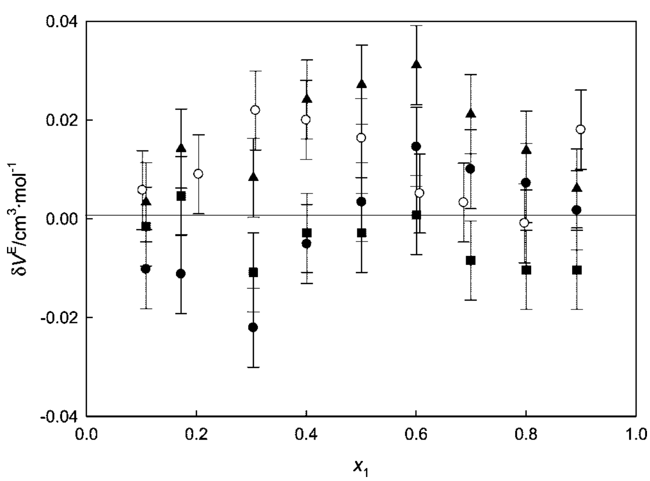

Figure 1. Fractional deviations $\delta V_m^E = V_m^E(\text{calcd}) - V_m^E(\text{exptl})$ of the excess molar volumes from calculated values from Rodriguez et al.[5] for MTBE (1) + nonane (2) (●, 288.15 K; ■, 293.15 K; ▲, 298.15 K) and from Piñeiro et al.[6] for MTBE (1) + decane (2) (O, 298.15 K). Error bars represent the uncertainty.

temperatures in this work. The positive deviations could be caused by the breaking of the self-association of the ether

Table 5. Comparison between Experimental Viscosities and Literature Values for Nonane and Decane

	η/mPa·s			
T/K	this work	lit.	this work	lit.
	Nonane		Decane	
273.15	0.972		1.312	
278.15	0.896		1.193	
283.15	0.828		1.091	
288.15	0.768		1.003	
293.15	0.716	0.716[24]	0.927	0.92[29]
298.15	0.669	0.665[25]	0.860	0.858[30]
303.15	0.628	0.626[26]	0.801	0.796[26]
308.15	0.590	0.589[26]	0.748	0.743[26]
313.15	0.555	0.545[27]	0.700	
318.15	0.522	0.523[12]	0.656	0.6573[12]
323.15	0.493	0.497[28]	0.615	
328.15	0.466	0.4665[14]	0.579	0.582[12]
333.15	0.442		0.546	
338.15	0.420	0.4188[14]	0.517	0.522[12]
343.15	0.399		0.490	
348.15	0.380		0.465	
353.15	0.362		0.443	
358.15	0.346			

Table 6. Parameters for the McAllister Equation

T/K	$\nu_{12}\cdot 10^{-6}$ / $m^2\cdot s^{-1}$	$\nu_{21}\cdot 10^{-6}$ / $m^2\cdot s^{-1}$	$\sigma\cdot 10^{-6}$ / $m^2\cdot s^{-1}$
	MTBE (1) + Nonane (2)		
273.15	0.8378	1.0743	$2.0\cdot 10^{-3}$
278.15	0.7949	1.0001	$1.6\cdot 10^{-3}$
283.15	0.7475	0.9389	$1.4\cdot 10^{-3}$
288.15	0.7062	0.8824	$1.7\cdot 10^{-3}$
	MTBE (1) + Decane (2)		
273.15	0.9960	1.3143	$2.3\cdot 10^{-3}$
278.15	0.9352	1.2193	$2.0\cdot 10^{-3}$
283.15	0.8803	1.1354	$2.4\cdot 10^{-3}$
288.15	0.8282	1.0632	$2.2\cdot 10^{-3}$

that allows a less dense packing of the molecules.[5] This packing effect decreases as the chain length of the molecule increases at constant temperature. Also, this packing effect decreases with temperature. The calculated excess molar volumes for both systems are in Tables 2 and 3, respectively. The excess molar volumes are represented with a Redlich–Kister-type equation.[1,2] The values of the parameters at each temperature together with their standard deviations from the fit are in Table 4. Our excess molar volume results are compared to those from Rodriguez et al.[5] and Piñeiro et al.[6] for the mixtures with nonane and decane, respectively. The average absolute deviation is 0.01 $cm^3\cdot mol^{-1}$ for both mixtures. Figure 1 shows the deviation of our data from equations developed by these authors.

A Cannon-Fenske capillary viscosimeter is used to measure the kinematic viscosities, and they are converted to dynamic viscosities using the experimental density measurements. Table 5 contains a comparison between the experimental viscosity measurements and other sources found in the literature. The kinematic viscosity of MBTE + nonane or decane is measured from (273.15 to 358.15) K. Viscosity measurements for these mixtures do not appear in the literature. Experimental measurements have been correlated using a three-body McAllister equation.[3] Table 6 has the values of υ_{12} and υ_{21} from (273.15 to 288.15) K. Dynamic viscosities at different temperatures and compositions appear in Tables 7 and 8. Viscosity deviations from these mixtures are practically zero and tend to be negative, so they behave like ideal solutions for equilibrium thermodynamic properties.

Table 7. Experimental Viscosities for Methyl *tert*-Butyl Ether (1) + Nonane (2)

	η/mPa·s								
T/K	$x_1 = 0.1006$	$x_1 = 0.2026$	$x_1 = 0.2995$	$x_1 = 0.4045$	$x_1 = 0.5003$	$x_1 = 0.6035$	$x_1 = 0.6998$	$x_1 = 0.7975$	$x_1 = 0.8971$
273.15	0.912	0.850	0.796	0.740	0.688	0.632	0.586	0.540	0.491
278.15	0.842	0.787	0.738	0.689	0.641	0.591	0.549	0.505	0.460
283.15	0.780	0.731	0.687	0.643	0.598	0.554	0.514	0.474	0.433
288.15	0.726	0.681	0.641	0.600	0.560	0.520	0.484	0.446	0.407
293.15	0.677	0.637	0.601	0.564	0.526	0.489	0.455	0.418	0.384
298.15	0.634	0.598	0.564	0.529	0.496	0.461	0.430	0.396	0.363
303.15	0.596	0.563	0.532	0.498	0.468	0.436	0.408	0.377	
308.15	0.560	0.531	0.502	0.470	0.443	0.413	0.386	0.357	
313.15	0.529	0.498	0.472	0.446	0.421	0.391	0.367		
318.15	0.498	0.471	0.446	0.422	0.401	0.372	0.348		
323.15	0.470	0.446	0.423	0.402	0.382	0.354			
328.15	0.445	0.424	0.402	0.383	0.364				
333.15	0.423	0.404	0.383	0.365	0.347				
338.15	0.402	0.386	0.366	0.348					
343.15	0.383	0.368	0.351						
348.15	0.366	0.352							
353.15	0.350	0.338							
358.15	0.335								

Table 8. Experimental Viscosities for Methyl *tert*-Butyl Ether (1) + Decane (2)

	η/mPa·s								
T/K	$x_1 = 0.1016$	$x_1 = 0.2002$	$x_1 = 0.3003$	$x_1 = 0.4013$	$x_1 = 0.4992$	$x_1 = 0.6005$	$x_1 = 0.7000$	$x_1 = 0.8005$	$x_1 = 0.8996$
273.15	1.200	1.093	1.004	0.909	0.822	0.741	0.659	0.584	0.513
278.15	1.092	1.002	0.924	0.841	0.765	0.689	0.615	0.547	0.481
283.15	1.001	0.923	0.855	0.779	0.713	0.643	0.575	0.513	0.452
288.15	0.923	0.856	0.793	0.726	0.664	0.601	0.540	0.481	0.426
293.15	0.855	0.795	0.743	0.678	0.622	0.563	0.507	0.454	0.402
298.15	0.797	0.742	0.692	0.635	0.584	0.531	0.479	0.428	0.379
303.15	0.744	0.695	0.650	0.597	0.550	0.500	0.452	0.405	0.358
308.15	0.698	0.653	0.606	0.562	0.519	0.474	0.428	0.382	
313.15	0.654	0.614	0.572	0.531	0.491	0.449	0.404	0.362	
318.15	0.614	0.579	0.540	0.503	0.462	0.426	0.383		
323.15	0.577	0.546	0.510	0.476	0.441	0.406	0.365		
328.15	0.546	0.517	0.483	0.451	0.418	0.386	0.350		
333.15	0.514	0.489	0.459	0.432	0.399	0.371			
338.15	0.489	0.466	0.438	0.413	0.382	0.359			
343.15	0.466	0.445	0.420	0.398	0.369				
348.15	0.443	0.424	0.402	0.383					
353.15	0.422	0.406	0.386	0.372					
358.15	0.407	0.388	0.372						

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