PHASE AND FLOW BEHAVIOR IN PETROLEUM PRODUCTION

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PREFACE

The study of phase relationships in the production of hydrocarbon mixtures is in considerable part the study of non-ideal systems. This is due primarily to the fact that water makes its appearance, and the aqueous phase may contain dissolved or entrained inorganic gases and/or mineral salts.

While light hydrocarbons per se behave in a more or less ideal manner, in the presence of water regions of immisci bility are set up which have a marked effect on the phase equilibrium. This and the other components which may appear make for most interesting combinations.

With heavier hydrocarbons, the increasing presence of oxygenated compounds also introduces an element of immiscibility. These are the asphaltic-types of materials which form dispersions and may otherwise be only partially miscible with hydrocarbons. The use of additives may further promote immiscibility and is indeed a feature of solvent refining.

While the behavior of petroleum fluids does not necessarily follow equilibrium, in many situations equilibrium is approached, and at the least forms a basis of reference.

Inasmuch as petroleum production involves fluid flow -- particularly flow through porous media -- developments in this sector are also investigated in detail. It is the anticipation that methodologies so introduced will greatly simplify the general reservoir unsteady-state depletion problem, and lead to improved correlations if not understanding of unsteady-state multiphase flow.

The sequence in the main first examines phase diagrams and the principles of phase equilibria and their correlation. This is followed by a treatment of the equations of unsteady-state flow and means for effecting solutions starting from volume and surface integrals, which may be correlated to unsteady-state behavior. The remaining chapters are devoted to the principles and applications of phase equilibria, particularly as applied to field processing and multiphase behavior, with the final chapter bringing up the subject of unconventional sources, with emphasis on gas hydrates and geopressured or geothermal aquifers.

In this effort techniques and methodologies developed in previous works by the author are adapted. These previous works include *Azeotropic and Extractive Distillation**, *The Concept of Energy: An Inquiry into Origins and Applications***, and *Heat Transfer Rate Analysis****. The applications are particularly appropriate to problems encountered in describing, correlating, and predicting phases and flow behavior in petroleum production -- in short, some of the more difficult problems encountered in reservoir analysis and field processing.

While one would always prefer to write a simple monograph, unfortunately the problems never seem so simple. It becomes the quandary of trying to come up with solutions for problems that do not in fact have solutions, only approximations. It is in this spirit, then, that this work is dedicated.

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*Hoffman, E.J., *Azeotropic and Extractive Distillation*, Interscience, New York, 1964. Second edition, Krieger, Huntington, NY, 1977.

**Hoffman, E.J., *The Concept of Energy: An Inquiry into Origins and Applications*, Ann Arbor Science, Ann Arbor, MI, 1977.

***Hoffman, E.J., *Heat Transfer Rate Analysis*, PennWell, Tulsa, OK, 1980.

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Chapter 1

INTRODUCTION

The fossil fuel "petroleum," in all its forms, is in the main composed of hydrocarbons: compounds of carbon and hydrogen -- though other elements may be bonded into the structure in minor or trace amounts, and still other compounds will be present, dissolved in or occurring as a distinct phase.

These hydrocarbons and such other constituents as present will exist variously in the gaseous and liquid states, and in sometimes semi-solid or solid states.

These naturally-occurring petroleum mixtures, with which we are to be concerned, rarely exist exclusively as the pure compound. Rather they are more likely to be part of a "complex mixture," a myriad of a near-infinity of compounds. Even natural gas, which is predominately methane, contains heavier components. Though the individual components may be readily distinguished by analysis up through perhaps C_7, there is still a higher-boiling constituency denoted mainly by a boiling-point curve or its equivalent.

Additionally, inorganic compounds are likely to be present, chiefly ubiquitous water which in the liquid phase will contain a host of dissolved solids. The inorganic gases are likely to be represented by carbon dioxide, hydrogen sulfide, and nitrogen, plus rarer species, even helium and argon in some instances.

While it is possible that a given mixture may occur in only one state or phase, the likelihood is that more than one phase exists. Consequently, the production of petroleum in its various states from geologic formations is dependent upon the phase equilibria that is maintained in the static formation or reservoir, and subsequently depends upon the dynamics of flow, both in the reservoir and in the well. There is a further symbiosis to the equilibrium that is simulated in field processing.

These equilibria not only occur among the hydrocarbons themselves, but between and among inorganic components present-- with inorganic gases, with water, and with dissolved mineral salts. The resultant distribution is dependent upon the temperature and pressure, the size of the reservoir, and the extent and proportions of the components -- the classical permutations among pressure, temperature, volume, and concentration in the study of phase equilibrium and changes that occur -- in other words, the thermodynamics of the system.

While refining includes both physical and chemical changes, here we will be confined to the physical and thermodynamic properties or variables that relate to phase equilibria, to fluid flow, and to field processing -- states and changes which for the most part do not involve chemical reactions.

It is the object in this work to consider all these facets as applied to the principal materials in place -- inorganic gases, water and salts as well as organic compounds and the interrelationships that occur within the static formations, during production, and in field processing. Of concern are the multiple phases that coexist -- the gaseous or vapor phase, liquids, and solids -- both in the conditions of equilibrium and in the dynamics of production. Conditions may range from high temperature geothermal reservoirs to the near-freezing and sub-freezing temperatures that yield gas hydrates in the arctic regions. In between are all the other conditions for the occurrence of natural gas, light and heavy crude oils, and tars and bitumens.

Other terms also make their appearance, depending in many ways on the methods of refining and production. Thus we also speak of natural gasoline, distillates, condensates, naphthas, fuel oils, lube oils, residuals, etc., each with a connotation of its own.

Equilibrium

Two or more phases may be present in most cases -- the qualification of heterogeneous equilibrium. A tautology, equilibrium between phases and heterogeneous equilibrium are one and the same -- the demarcation of multiphase systems which in the limit become a single phase.

In various combinations, there may be equilibrium between and among vapor, liquids, and solids. Most are obvious: the gas-liquid equilibriums of hydrocarbons, or the liquid-liquid equilibriums of hydrocarbons and water. What sometimes appears as a single phase, however, may exhibit a peculiar heterogeneity -- e.g., emulsions of oil and water, and dispersions involving asphalts, tars or bitumens.

1.1 PETROLEUM MIXTURES

The fossil fuels, which are of biological origin, range from gaseous and highly volatile mixtures, through the liquid and semi-solid, to unmistakably solid materials. The organic components are by definition composed of carbon, hydrogen and oxygen in varying proportions, with the remainder the inorganic. The distinction cannot be clear-cut, since other elements, particularly nitrogen and sulfur, may be bonded into the C-H-O structure.

Naturally-occurring gaseous and liquid mixtures predominately of hydrocarbons are generically spoken of as petroleum. The term requires further distinction as previously indicated. Thus there are the terms gas and oil, or natural gas and crude oil. Or in order of decreasing volatility, there are the terms light and heavy oils, tars or asphalts, and bitumens. The bitumens comprise the end of the scale, the solids or solid-residues. As the material decreases in volatility, however, an increase in oxygen content (and sulfur and nitrogen) changes the character and makeup of the mixture.

As inferred, distinction is not then always so clear since coals, oil shales and other bituminous materials are also of organic origin. It is sometimes a matter of degree, conditions, and source, and the processes of formation.

Distribution of Components

The organic components of a petroleum reservoir will exist in either the gaseous, liquid, semi-solid or solid states. Examples would range through natural gas, oil (crude oil), highly viscous oils or tars or even solids -- and, at low temperature, hydrates, the clathrate-type structures composed of hydrocarbons bound with water which form as solids at freezing or near-freezing temperatures, depending upon the pressure.

The organic constituents are composed primarily of hydro - carbons. However, with increasing molecular weight, oxygenated compounds make an appearance, and sulfur and nitrogen are also bound into the structure in varying degree -- partial evidence of the original organic source.

These states of matter may co-exist as phases at equilibrium or near-equilibrium. Moreover, additional components of inorganic origin are most usually present. The inorganic constituents notably include water, in the liquid form and distributed between the other phases. The aqueous phase will usually contain mineral salts. Additionally, inorganic gases may occur, which are distributed between the phases according to solubility.

A listing of the principal components likely to be encountered would include the following:

N_2

CO_2

H_2S

Hydrocarbons: C_mH_n

Oxygenated Compounds: $C_mH_nO_p$

Organic Sulfur and Nitrogen: $C_mH_nO_p - S_j - N_k$

H_2O

Mineral Salts:

Alkali chlorides	Alkaline earth chlorides
carbonates	carbonates
sulfides	sulfides
sulfates	sulfates

These salts would include the acid carbonates, acid sulfides, and acid sulfates as well, depending upon the pH.

Nitrogen represents the inert and noble gases, and includes helium principally. While CO_2 and H_2S are both acid gases, there are enough dissimilarities to list them apart. Though carbonyl sulfide may form ($CO_2 + H_2S = COS + H_2O$), it will not be listed. Neither will be carbon disulfide. Mercaptans are a probability but are not listed separately.

Though a variety of salts can be present, the preponderance of inactive salts (at essentially neutral reservoir conditions) will be alkaline earth chlorides and sulfates (and bisulfates). The principle active salt would be alkaline carbonates (and bicarbonates), since CO_2 may be present. Since hydrogen sulfide may also be present, however, provision is also made for the sulfides (and bisulfides).

Sodium best represents the alkali ion, calcium, the alkaline-earth ion, though other members of these families are also present. It should be noted that the alkaline earth salts display a limited solubility in the form of the sulfate and carbonate, though the bisulfate and bicarbonate (or acid sulfate and acid carbonate) are markedly soluble. The pH may be regarded as controlling -- determining the degree to which the salt exists in the acid form.

Compounds of aluminum and silicon, though in great proportions in the earth's crust, will for the most part remain insoluble at the conditions encountered.

Hydrocarbons

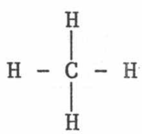
The hydrocarbons range from methane through propane, through butanes, pentanes, hexanes and heptanes, on up the list. Moreover, the hydrocarbons heavier than propane may in part be present as isomers, compounds with the same molecular weight but a different structure.

A listing of lighter hydrocarbons identified in natural gas and petroleum mixtures is presented in Table 1.1 along with physical properties. The isomers for C_1 through C_7 are given plus other hydrocarbons and assorted other compounds of interest.

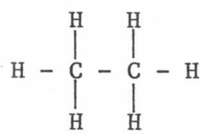
While the lower or lower-boiling hydrocarbons can be represented as distinct components in an analysis, the higher-boiling compounds can only be included as a fraction -- that is, a distillation cut where boiling point is plotted versus the percent distilled over (a boiling-point curve).

Finally, hydrocarbons exist in a variety of structures. These may be classified as paraffinic or saturated, olefinic or unsaturated, aromatic, and naphthenic.

Paraffinic compounds have all the extra carbon bonds filled with hydrogen. Symbolically,



methane



ethane

etc.

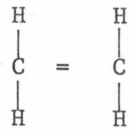
Table 1.1 Physical Constants of Hydrocarbons (1)

No.	Compound	Formula	Molecular weight	Boiling point °F., 14.696 psia	Vapor pressure, 100°F., psia	Freezing point, °F., 14.696 psia	Critical constants: Pressure, psia	Critical constants: Temperature, °F.	Critical constants: Volume, cu ft/lb
1	Methane	CH_4	16.043	−258.69	(5000)	−296.46[d]	667.8	−116.63	0.0991
2	Ethane	C_2H_6	30.070	−127.48	(800)	−297.89[d]	707.8	90.09	0.0788
3	Propane	C_3H_8	44.097	−43.67	190.	−305.84[d]	616.3	206.01	0.0737
4	n-Butane	C_4H_{10}	58.124	31.10	51.6	−217.05	550.7	305.65	0.0702
5	Isobutane	C_4H_{10}	58.124	10.90	72.2	−255.29	529.1	274.98	0.0724
6	n-Pentane	C_5H_{12}	72.151	96.92	15.570	−201.51	488.6	385.7	0.0675
7	Isopentane	C_5H_{12}	72.151	82.12	20.44	−255.83	490.4	369.10	0.0679
8	Neopentane	C_5H_{12}	72.151	49.10	35.9	2.17	464.0	321.13	0.0674
9	n-Hexane	C_6H_{14}	86.178	155.72	4.956	−139.58	436.9	453.7	0.0688
10	2-Methylpentane	C_6H_{14}	86.178	140.47	6.767	−244.63	436.6	435.83	0.0681
11	3-Methylpentane	C_6H_{14}	86.178	145.89	6.098	—	453.1	448.3	0.0681
12	Neohexane	C_6H_{14}	86.178	121.52	9.856	−147.72	446.8	420.13	0.0667
13	2,3-Dimethylbutane	C_6H_{14}	86.178	136.36	7.404	−199.38	453.5	440.29	0.0665
14	n-Heptane	C_7H_{16}	100.205	209.17	1.620	−131.05	396.8	512.8	0.0691
15	2-Methylhexane	C_7H_{16}	100.205	194.09	2.271	−180.89	396.5	495.00	0.0673
16	3-Methylhexane	C_7H_{16}	100.205	197.32	2.130	—	408.1	503.78	0.0646
17	3-Ethylpentane	C_7H_{16}	100.205	200.25	2.012	−181.48	419.3	513.48	0.0665
18	2,2-Dimethylpentane	C_7H_{16}	100.205	174.54	3.492	−190.86	402.2	477.23	0.0665
19	2,4-Dimethylpentane	C_7H_{16}	100.205	176.89	3.292	−182.63	396.9	475.95	0.0668
20	3,3-Dimethylpentane	C_7H_{16}	100.205	186.91	2.773	−210.01	427.2	505.85	0.0662
21	Triptane	C_7H_{16}	100.205	177.58	3.374	−12.82	428.4	496.44	0.0636
22	n-Octane	C_8H_{18}	114.232	258.22	0.537	−70.18	360.6	564.22	0.0690
23	Diisobutyl	C_8H_{18}	114.232	228.39	1.101	−132.07	360.6	530.44	0.0676
24	Isooctane	C_8H_{18}	114.232	210.63	1.708	−161.27	372.4	519.46	0.0656
25	n-Nonane	C_9H_{20}	128.259	303.47	0.179	−64.28	332.	610.68	0.0684
26	n-Decane	$C_{10}H_{22}$	142.286	345.48	0.0597	−21.36	304.	652.1	0.0679
27	Cyclopentane	C_5H_{10}	70.135	120.65	9.914	−136.91	653.8	461.5	0.059
28	Methylcyclopentane	C_6H_{12}	84.162	161.25	4.503	−224.44	548.9	499.35	0.0607
29	Cyclohexane	C_6H_{12}	84.162	177.29	3.264	43.77	591.	536.7	0.0586
30	Methylcyclohexane	C_7H_{14}	98.189	213.68	1.609	−195.87	503.5	570.27	0.0600
31	Ethylene	C_2H_4	28.054	−154.62	—	−272.45[d]	729.8	48.58	0.0737
32	Propene	C_3H_6	42.081	−53.90	226.4	−301.45[d]	669.	196.9	0.0689
33	1-Butene	C_4H_8	56.108	20.75	63.05	−301.63[d]	583.	295.6	0.0685
34	Cis-2-Butene	C_4H_8	56.108	38.69	45.54	−218.06	610.	324.37	0.0668
35	Trans-2-Butene	C_4H_8	56.108	33.58	49.80	−157.96	595.	311.86	0.0680
36	Isobutene	C_4H_8	56.108	19.59	63.40	−220.61	580.	292.55	0.0682
37	1-Pentene	C_5H_{10}	70.135	85.93	19.115	−265.39	590.	376.93	0.0697
38	1,2-Butadiene	C_4H_6	54.092	51.53	(20.)	−213.16	(653.)	(339.)	(0.0649)
39	1,3-Butadiene	C_4H_6	54.092	24.06	(60.)	−164.02	628.	306.	0.0654
40	Isoprene	C_5H_8	68.119	93.30	16.672	−230.74	(558.4)	(412.)	(0.0650)
41	Acetylene	C_2H_2	26.038	−119[e]	—	−114.[d]	890.4	95.31	0.0695
42	Benzene	C_6H_6	78.114	176.17	3.224	41.96	710.4	552.22	0.0531
43	Toluene	C_7H_8	92.141	231.13	1.032	−138.94	595.9	605.55	0.0549
44	Ethylbenzene	C_8H_{10}	106.168	277.16	0.371	−138.91	523.5	651.24	0.0564
45	o-Xylene	C_8H_{10}	106.168	291.97	0.264	−13.30	541.4	675.0	0.0557
46	m-Xylene	C_8H_{10}	106.168	282.41	0.326	−54.12	513.6	651.02	0.0567
47	p-Xylene	C_8H_{10}	106.168	281.05	0.342	55.86	509.2	649.6	0.0572
48	Styrene	C_8H_8	104.152	293.29	(0.24)	−23.10	580.	706.0	0.0541
49	Isopropylbenzene	C_9H_{12}	120.195	306.34	0.188	−140.82	465.4	676.4	0.0570
50	Methyl Alcohol	CH_4O	32.042	148.1(2)	4.63(22)	−143.82(22)	1174.2(21)	462.97(21)	0.0589(21)
51	Ethyl Alcohol	C_2H_6O	46.069	172.92(22)	2.3(7)	−173.4(22)	925.3(21)	469.58(21)	0.0580(21)
52	Carbon Monoxide	CO	28.010	−313.6(2)	—	−340.6(2)	507.(17)	−220.(17)	0.0532(17)
53	Carbon Dioxide	CO_2	44.010	−109.3(2)	—	—	1071.(17)	87.9(23)	0.0342(23)
54	Hydrogen Sulfide	H_2S	34.076	−76.6(24)	394.0(6)	−117.2(7)	1306.(17)	212.7(17)	0.0459(24)
55	Sulfur Dioxide	SO_2	64.059	14.0(7)	88.(7)	−103.9(7)	1145.(24)	315.5(17)	0.0306(24)
56	Ammonia	NH_3	17.031	−28.2(24)	212.(7)	−107.9(2)	1636.(17)	270.3(24)	0.0681(17)
57	Air	N_2O_2	28.964	−317.6(2)	—	—	547.(2)	−221.3(2)	0.0517(3)
58	Hydrogen	H_2	2.016	−423.0(24)	—	−434.8(24)	188.1(17)	−399.8(17)	0.5167(24)
59	Oxygen	O_2	31.999	−297.4(2)	—	−361.8(24)	736.9(24)	−181.1(17)	0.0382(24)
60	Nitrogen	N_2	28.013	−320.4(2)	—	−346.0(24)	493.0(24)	−232.4(24)	0.0514(17)
61	Chlorine	Cl_2	70.906	−29.3(24)	158.(7)	−149.8(24)	1118.4(24)	291.(17)	0.0281(17)
62	Water	H_2O	18.015	212.0	0.9492(12)	32.0	3208.(17)	705.6(17)	0.0500(17)
63	Helium	He	4.003	—	—	—	—	—	—
64	Hydrogen Chloride	HCl	36.461	−121(16)	925.(7)	−173.6(16)	1198.(17)	124.5(17)	0.0208(17)

Table 1.1 (Cont.)

Density of liquid; 60°F., 14.696 psia							Gas density, 60°F. 14.696 psia Ideal gas*			Specific heat 60°F., 14.696 psia Cp, Btu/lb/°F.		
Specific gravity 60°F./60°F.a,b	lb/gal* a (Wt in vacuum)	lb/gal* a,c (Wt in air)	Gal/lb Mole*	Temperature Coefficient of density* a	Pitzer acentric factor (18)	Compressibility factor of real gas, Z 14.696 psia, 60°F.	Specific gravity Air = 1*	cu ft gas/lb*	cu ft gas/gal liquid*	Ideal gas	Liquid	No.
0.3[i]	2.5[i]	2.5[i]	6.4[i]	—	0.0104	0.9981	0.5539	23.65	59.[i]	0.5266	—	1
0.3564[h]	2.971[h]	2.962[h]	10.12[h]	—	0.0986	0.9916	1.0382	12.62	37.5[h]	0.4097	0.9256	2
0.5077[h]	4.233[h]	4.223[h]	10.42[h]	0.00152[h]	0.1524	0.9820	1.5225	8.606	36.43[h]	0.3881	0.5920	3
0.5844[h]	4.872[h]	4.865[h]	11.93[h]	0.00117[h]	0.2010	0.9667	2.0068	6.529	31.81[h]	0.3867	0.5636	4
0.5631[h]	4.695[h]	4.686[h]	12.38[h]	0.00119[h]	0.1848	0.9696	2.0068	6.529	30.65[h]	0.3872	0.5695	5
0.6310	5.261	5.251	13.71	0.00087	0.2539	0.9549	2.4911	5.260	27.67	0.3883	0.5441	6
0.6247	5.208	5.199	13.85	0.00090	0.2223	0.9544	2.4911	5.260	27.39	0.3827	0.5353	7
0.5967[h]	4.975[h]	4.965[h]	14.50[h]	0.00104[h]	0.1969	0.9510	2.4911	5.260	26.17[h]	(0.3866)	0.554	8
0.6640	5.536	5.526	15.57	0.00075	0.3007	—	2.9753	4.404	24.38	0.3864	0.5332	9
0.6579	5.485	5.475	15.71	0.00078	0.2825	—	2.9753	4.404	24.15	0.3872	0.5264	10
0.6689	5.577	5.568	15.45	0.00075	0.2741	—	2.9753	4.404	24.56	0.3815	0.507	11
0.6540	5.453	5.443	15.81	0.00078	0.2369	—	2.9753	4.404	24.01	0.3809	0.5165	12
0.6664	5.556	5.546	15.51	0.00075	0.2495	—	2.9753	4.404	24.47	0.378	0.5127	13
0.6882	5.738	5.728	17.46	0.00069	0.3498	—	3.4596	3.787	21.73	0.3875	0.5283	14
0.6830	5.694	5.685	17.60	0.00068	0.3336	—	3.4596	3.787	21.57	(0.390)	0.5223	15
0.6917	5.767	5.757	17.38	0.00069	0.3257	—	3.4596	3.787	21.84	(0.390)	0.511	16
0.7028	5.859	5.850	17.10	0.00070	0.3095	—	3.4596	3.787	22.19	(0.390)	0.5145	17
0.6782	5.654	5.645	17.72	0.00072	0.2998	—	3.4596	3.787	21.41	(0.395)	0.5171	18
0.6773	5.647	5.637	17.75	0.00072	0.3048	—	3.4596	3.787	21.39	0.3906	0.5247	19
0.6976	5.816	5.807	17.23	0.00065	0.2840	—	3.4596	3.787	22.03	(0.395)	0.502	20
0.6946	5.791	5.782	17.30	0.00069	0.2568	—	3.4596	3.787	21.93	0.3812	0.4995	21
0.7068	5.893	5.883	19.39	0.00062	0.4018	—	3.9439	3.322	19.58	(0.3876)	0.5239	22
0.6979	5.819	5.810	19.63	0.00065	0.3596	—	3.9439	3.322	19.33	(0.373)	0.5114	23
0.6962	5.804	5.795	19.68	0.00065	0.3041	—	3.9439	3.322	19.28	0.3758	0.4892	24
0.7217	6.017	6.008	21.32	0.00063	0.4455	—	4.4282	2.959	17.80	0.3840	0.5228	25
0.7342	6.121	6.112	23.24	0.00055	0.4885	—	4.9125	2.667	16.33	0.3835	0.5208	26
0.7504	6.256	6.247	11.21	0.00070	0.1955	0.9657	2.4215	5.411	33.85	0.2712	0.4216	27
0.7536	6.283	6.274	13.40	0.00071	0.2306	—	2.9057	4.509	28.33	0.3010	0.4407	28
0.7834	6.531	6.522	12.89	0.00068	0.2133	—	2.9057	4.509	29.45	0.2900	0.4332	29
0.7740	6.453	6.444	15.22	0.00063	0.2567	—	3.3900	3.865	24.94	0.3170	0.4397	30
—	—	—	—	—	0.0868	0.9938	0.9686	13.53	—	0.3622	—	31
0.5220[h]	4.352[h]	4.343[h]	9.67[h]	0.00189[h]	0.1405	0.9844	1.4529	9.018	39.25[h]	0.3541	0.585	32
0.6013[h]	5.013[h]	5.004[h]	11.19[h]	0.00116[h]	0.1906	0.9704	1.9372	6.764	33.91[h]	0.3548	0.535	33
0.6271[h]	5.228[h]	5.219[h]	10.73[h]	0.00098[h]	0.1953	0.9661	1.9372	6.764	35.36[h]	0.3269	0.5271	34
0.6100[h]	5.086[h]	5.076[h]	11.03[h]	0.00107[h]	0.2220	0.9662	1.9372	6.764	34.40[h]	0.3654	0.5351	35
0.6004[h]	5.006[h]	4.996[h]	11.21[h]	0.00120[h]	0.1951	0.9689	1.9372	6.764	33.86[h]	0.3701	0.549	36
0.6457	5.383	5.374	13.03	0.00089	0.2925	0.9550	2.4215	5.411	29.13	0.3635	0.5196	37
0.658[h]	5.486[h]	5.470[h]	9.86[h]	0.00098[h]	0.2485	(0.969)	1.8676	7.016	38.49[h]	0.3458	0.5408	38
0.6272[h]	5.229[h]	5.220[h]	10.34[h]	0.00113[h]	0.1955	(0.965)	1.8676	7.016	36.69[h]	0.3412	0.5079	39
0.6861	5.720	5.711	11.91	0.00086	0.2323	(0.962)	2.3519	5.571	31.87	0.357	0.5192	40
0.615[k]	—	—	—	—	0.1803	0.9925	0.8990	14.57	—	0.3966	—	41
0.8844	7.373	7.365	10.59	0.00066	0.2125	0.929(15)	2.6969	4.858	35.82	0.2429	0.4098	42
0.8718	7.268	7.260	12.68	0.00060	0.2596	0.903(21)	3.1812	4.119	29.94	0.2598	0.4012	43
0.8718	7.268	7.259	14.61	0.00054	0.3169	—	3.6655	3.574	25.98	0.2795	0.4114	44
0.8848	7.377	7.367	14.39	0.00055	0.3023	—	3.6655	3.574	26.37	0.2914	0.4418	45
0.8687	7.243	7.234	14.66	0.00054	0.3278	—	3.6655	3.574	25.89	0.2782	0.4045	46
0.8657	7.218	7.209	14.71	0.00054	0.3138	—	3.6655	3.574	25.80	0.2769	0.4083	47
0.9110	7.595	7.586	13.71	0.00057	—	—	3.5959	3.644	27.67	0.2711	0.4122	48
0.8663	7.223	7.214	16.64	0.00054	0.2862	—	4.1498	3.157	22.80	0.2917	(0.414)	49
0.796(3)	6.64	6.63	4.83	—	—	—	1.1063	11.84	78.6	0.3231[v](24)	0.594(7)	50
0.794(3)	6.62	6.61	6.96	—	—	—	1.5906	8.237	54.5	0.3323[v](24)	0.562(7)	51
0.801[m](8)	6.68[m]	6.67[m]	4.19[m]	—	0.041	0.9995(15)	0.9671	13.55	—	0.2484(13)	—	52
0.827[h](6)	6.89[h]	6.88[h]	6.38[h]	—	0.225	0.9943(15)	1.5195	8.623	59.5[h]	0.1991(13)	—	53
0.79[h](6)	6.59[h]	6.58[h]	5.17[h]	—	0.100	0.9903(15)	1.1765	11.14	73.3[h]	0.238(4)	—	54
1.397[h](14)	11.65[h]	11.64[h]	5.50[h]	—	0.246	—	2.2117	5.924	69.0[h]	0.145(7)	0.325[h](7)	55
0.6173(11)	5.15	5.14	3.31	—	0.255	—	0.5880	22.28	114.7	0.5002(10)	1.114[h](7)	56
0.856[m](8)	7.14[m]	7.13[m]	4.06[m]	—	—	0.9996(15)	1.0000	13.10	—	0.2400(9)	—	57
0.07[m](3)	—	—	—	—	0.000	1.0006(15)	0.0696	188.2	—	3.408(13)	—	58
1.140(25)	9.50[m]	9.49[m]	3.37[m]	—	0.0213	—	1.1048	11.86	—	0.2188(13)	—	59
0.810(26)	6.75[m]	6.74[m]	4.15[m]	—	0.040	0.9997(15)	0.9672	13.55	—	0.2482(13)	—	60
1.414(14)	11.79	11.78	6.01	—	—	—	2.4481	5.352	63.1	0.119(7)	—	61
1.000	8.337	8.328	2.16	—	0.348	—	0.6220	21.06	175.6	0.4446(13)	1.0009(7)	62
—	—	—	—	—	—	—	—	—	—	—	—	63
0.8558(14)	7.135	7.126	5.11	0.00335*	—	—	1.2588	10.41	74.3	0.190(7)	—	64

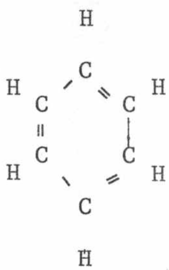
The compound may be straight chain or branched chain (isomers).
Olefinic compounds have unfilled carbon bonds:



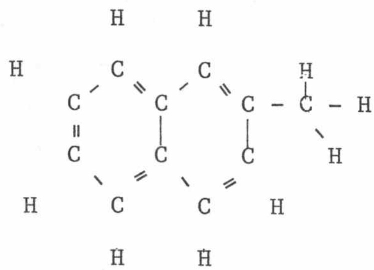
etc.

ethylene (or ethene)

Aromatic compounds are characterized by the benzene six-carbon ring structure, containing alternate points of saturation and unsaturation:



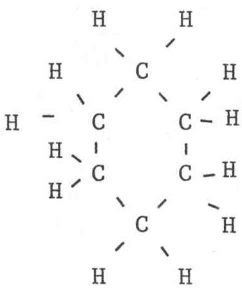
benzene



Etc.

0 - methyl xylene

Naphthenic compounds are a catchall. More specifically, they involve saturates and branched chains which loop or cycle upon themselves. Thus cyclopentane is naphthenic:



cyclopentane

Table 1.2 Types of Hydrocarbons (2)

(From *Chemical Technology of Petroleum* by W.A. Gruse and D.R. Stevens. Copyright 1942 by McGraw-Hill. Used with the permission of McGraw-Hill Book Company.)

Number	Formula	Name and type	Boiling point, 1 atm., °C.	Estimated relative amount by volume*
		Paraffinic		
1	CH_4	Methane	−161.7	†
2	C_2H_6	Ethane	− 88.6	†
3	C_3H_8	Propane	− 42.2	†
4	C_4H_{10}	Isobutane	− 12.1	†
5	C_4H_{10}	*n*-Butane	− 0.5	†
6	C_5H_{12}	2-Methylbutane	27.9	†
7	C_5H_{12}	*n*-Pentane	36.1	†
8	C_6H_{14}	2,3-Dimethylbutane	58.0	0.06
9	C_6H_{14}	2-Methylpentane	60.3	0.1_2
10	C_6H_{14}	3-Methylpentane	63.3	0.2_5
11	C_6H_{14}	*n*-Hexane	68.7	0.7
12	C_7H_{16}	2,2-Dimethylpentane	78.9	0.04
13	C_7H_{16}	2-Methylhexane	90.0	0.3_1
14	C_7H_{16}	3-Methylhexane	92.0	0.2_4
15	C_7H_{16}	*n*-Heptane	98.4	1.1
16	C_8H_{18}	2-Methylheptane	117.2	0.5
17	C_8H_{18}	*n*-Octane	125.6	1.0
18	C_9H_{20}	2,6-Dimethylheptane	135.2	0.1
19	C_9H_{20}	2,3-Dimethylheptane‡	140.8	0.05
20	C_9H_{20}	4-Methyloctane	142.4	0.06
21	C_9H_{20}	2-Methyloctane	143.3	0.2
22	C_9H_{20}	3-Methyloctane	144.2	0.06
23	C_9H_{20}	*n*-Nonane	150.7	1.0
24	$C_{10}H_{22}$	*n*-Decane	174.0	1.0
25	$C_{12}H_{26}$	*n*-Dodecane	216.3	1.0^E
		Naphthenic		
1	C_5H_{10}	Cyclopentane	49.5	†
2	C_6H_{12}	Methylcyclopentane	71.9	0.2_5
3	C_6H_{12}	Cyclohexane	80.8	0.3_5
4	C_7H_{14}	1,1-Dimethylcyclopentane	87.5	0.05
5	C_7H_{14}	Trans-1,3-Dimethylcyclopentane	90.9	0.2_3
6	C_7H_{14}	Trans-1,2-Dimethylcyclopentane	91.9	0.3_4
7	C_7H_{14}	Methylcyclohexane	100.9	0.3_5
8	C_8H_{16}	Octanaphthene	119.8	0.2
9	C_8H_{16}	1,3-Dimethylcyclohexane	120.3	
10	C_8H_{16}	1,2-Dimethylcyclohexane‡	123.4	0.04
11	C_8H_{16}	Ethylcyclohexane	131.8	0.1
12	C_9H_{18}	Nonanaphthene	136.7	0.1
13	C_9H_{18}	1,2,4-Trimethylcyclohexane	141.2	0.08
Number	Formula	Name and type	Boiling point, 1 atm., °C.	Estimated relative amount by volume*
		Aromatic		
1	C_6H_6	Benzene	80.1	0.08
2	C_7H_8	Toluene	110.6	0.3
3	C_8H_{10}	Ethylbenzene	136.2	0.03
4	C_8H_{10}	*p*-Xylene	138.4	0.04
5	C_8H_{10}	*m*-Xylene	139.2	0.1_2
6	C_8H_{10}	*o*-Xylene	144.4	0.1_2
7	C_9H_{12}	Isopropylbenzene	152.4	0.03
8	C_9H_{12}	*n*-Propylbenzene	159.5	0.03
9	C_9H_{12}	1-Methyl-3-ethylbenzene	161.3	§
10	C_9H_{12}	1-Methyl-4-ethylbenzene	161.9	§
11	C_9H_{12}	1,3,5-Trimethylbenzene	164.6	0.04
12	C_9H_{12}	1-Methyl-2-ethylbenzene	164.7	§
13	C_9H_{12}	1,2,4-Trimethylbenzene	169.2	0.2
14	C_9H_{12}	1,2,3-Trimethylbenzene	176.1	0.06
15	$C_{10}H_{14}$	1,2,3,4-Tetramethylbenzene	205.0	0.078^E
16	$C_{10}H_{12}$	5,6,7,8-Tetrahydronaphthalene	207.6	0.02^E
17	$C_{10}H_8$	Naphthalene	281.0	0.03^E
18	$C_{11}H_{10}$	2-Methylnaphthalene	241.1	0.13^E
19	$C_{11}H_{10}$	1-Methylnaphthalene	244.8	0.06^E
20	$C_{11}H_{14}$	1-Methyl-5,6,7,8-tetrahydronaphthalene	243.3	0.05
21	$C_{11}H_{14}$	2-Methyl-5,6,7,8-tetrahydronaphthalene	229.0	0.05