Essay 2

Physical Background of Heat Conduction

2.1 Physical Nature

The first topic in our course is heat conduction. An illustration of heat conduction is displayed in Fig. 2.1. It can easily be understood that the copper rod is an effective pathway for heat flow from the flame of the candle to the hand of the person who is holding the rod. However, by observation of the heat-conducting rod, nothing can be seen of the heat that is flowing. Conduction is the mode of heat flow that cannot be directly observed. Its occurrence can only be inferred from the effects that heat flow has on the objects that are involved in the conduction process.

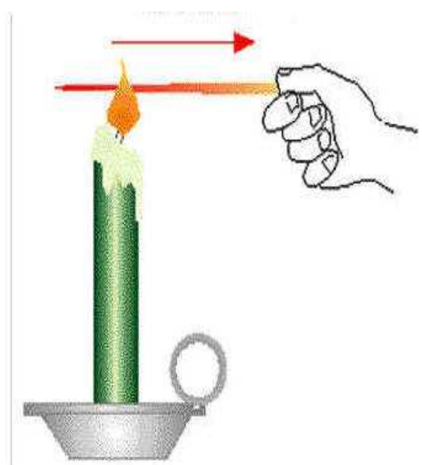

Fig. 2. 1 Illustration of heat conduction. The person who is holding the copper rod is experiencing the heat that is conducted from the flame to his/her hand.

The conduction process occurs at the molecular or sub-molecular scale. In metallic objects, where there are free electrons, the unrestricted movement of the free electrons causes them to be effective heat carriers. On the other hand, dielectric materials only contain bound electrons, but not free electrons. For such materials, heat conduction occurs by means of molecules and atoms.

To best explain the heat conduction process, it is useful to recall some facts from basic physics. First, the motion of molecules and sub-molecular particles ceases at absolute zero. At temperatures above absolute zero, the mean kinetic energy of a cloud of small particles increases with increasing temperature. As a consequence, the higher the temperature, the greater is the kinetic energy. Another fact from basic physics teaches the outcome of collisions between particles which possess different magnitudes of kinetic energy. That outcome is that the collision increases the kinetic energy of the particle which initially possesses the lower kinetic energy, and decreases the kinetic energy of the particle whose kinetic energy is initially higher. Since kinetic energy can be regarded as equivalent to temperature, the collision process increases the temperature of one of the colliding particles and decreases the temperature of the other.

This phenomenon is illustrated in Fig. 2.2. That figure consists of three parts, (a), (b), and (c). Each of the parts shows a cluster of particles. In part (a), one of the particles is shown by color to possess a higher temperature and a higher kinetic energy than the others. The higher temperature particle is receiving heat continuously from an external source. Part (b), which corresponds to a time that is slightly later than that of part (a), shows the effect of collisions between the higher temperature particle and its immediate neighbors. Those collisions raise the temperatures of the immediate neighbors. With the further passage of time, the immediate neighbors collide with their immediate neighbors, thereby increasing the temperatures of the latter.

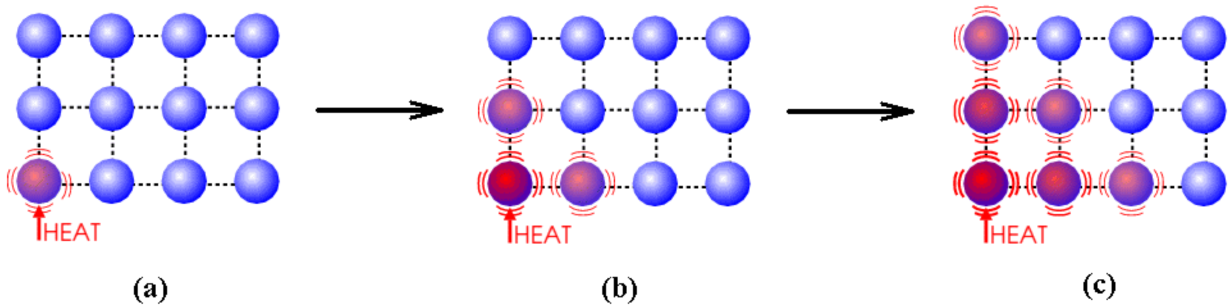

Fig. 2. 2 Schematic illustration of the process of heat conduction. Collisions cause a transfer of kinetic energy which, in effect, is equivalent to the transfer of heat.

2.2 Thermal Conductivity vs. Electrical Conductivity

The effectiveness by which heat is transferred between hotter and cooler zones depends on a material property called the *thermal conductivity*. Materials which contain free electrons are the best conductors of heat and possess a high value of the thermal conductivity. In fact, aside from one exception, the very best heat-conducting materials are also the very best conductors of electricity. In the absence of free electrons, the magnitude of the thermal conductivity is much lower than that of free-electron-possessing materials. However, the thermal conductivity is never zero for any material. This non-zero thermal conductivity law does not hold for electric conductivity.

To illustrate this fact, suppose that a person is doing some handyman electrical wiring at home and does not have the proper tape or wire nuts to cover the joining of two wires. The person twists the two wires together and throws a switch to initiate current flow. If the person is a risk taker, he/she might grasp the joint and feel a shock, the magnitude of which depends on the surface on which the person is standing. If, on the other hand, the person grasps the joint with a piece of paper, it is unlikely that any shock would be felt. Next, suppose an experiment is to be performed to determine the thermal insulating properties of paper. For this purpose, a penpoint-type soldering iron will be used. Before the soldering iron is plugged into a wall outlet, a piece of paper is stretched over the pointed end. When the current flow is initiated, an unpleasant burn will result if the person would grasp the paper cover. This example indicates that electric insulators and thermal insulators are not correlated.

The process of heat conduction in thermal insulators has no counterpart for electric insulators. That heat conduction process for thermal insulators can be illustrated by making reference to Fig. 2.2. In this regard, now envision that the dashed lines which interconnect the individual spheres (atoms) are elastic springs which permit the atoms to vibrate but which limit the extent of their motion. As the atoms vibrate, they collide and exchange kinetic energy. This is the process of heat conduction in the absence of free electrons.

2.3 Tables of Thermal Conductivity Values

Values of the thermal conductivity of metals and dielectric materials are conveyed in Tables 2.1 and 2.2, respectively. It is interesting to point out that the values of the thermal conductivities for diamond and pyrolitic graphite, both excellent electric insulators, far exceed those for the best thermal conducting metals.

Table 2. 1 Thermal conductivity of common metals as a function of temperature. $[\frac{W}{m \cdot K}]$

Metal	Temperature, K								
	200	300	400	500	600	800	1000	1200	1500
Aluminum									
Pure	237	237	240	236	231	218			
Duralumin	138	174	187	188					
Alloy 195, cast		168	174	180	185				
Copper									
Pure	413	401	393	386	379	366	352	339	
Commercial bronze	42	52	52	55					
Brass	74	111	134	143	146	150			
German silver		116	135	145	147				
Gold	323	317	311	304	298	284	270	255	
Iron									
Armco	81	73	66	59	53	42	32	29	31
Cast		51	44	39	36	27	23		
Carbon steels									
AISI 1010		64	59	54	49	39	31		
AISI 1042		52	50	48	45	37	29	26	30
AISI 4130		43	42	41	40	37	31	27	31
Stainless steels									
AISI 302		15	17	19	20	23	25		
AISI 304	13	15	17	18	20	23	25		
AISI 316		13	15	17	18	21	24		
AISI 410	25	25	26	27	27	29			
Lead	37	35	34	33	31				
Magnesium									
Pure	199	156	153	151	149	146			
Alloy A8			84						
Nickel									
Pure	105	91	80	72	66	68	72	76	83
Inconel-X-750	10.3	11.7	13.5	15.1	17.0	20.5	24.0	27.6	30.0
Nichrome		13	14	16	17	21			
Platinum	73	72	72	72	73	76	79	83	90
Silver	420	429	425	419	412	396	379	361	
Tantalum	58	58	58	59	59	59	60	61	62
Tin	73	67	62	60					
Titanium									
Pure	25	22	20	20	19	19	21	22	25
Ti-6Al-4V		5.8							
Tungsten	185	174	159	146	137	125	118	112	106
Zirconium									
Pure	25	23	22	21	21	21	23	26	29
Zircaloy-4	13.3	14.2	15.2	16.2	17.2	19.2	21.2	23.2	

Table 2. 2 Thermal conductivity of dielectric materials as a function of temperature.

Dielectric	T K	k W/m K
Aluminum oxide, Al_2O_3		
Sapphire	300	46
Alumina	300	36
	400	27
	600	16
	1000	7.6
	1500	5.4
Carbon		
Diamond (type IIb)	300	1300
ATJ-S graphite	300	98
	1000	55
	2000	38
	3000	33
Pyrolytic graphite	300	1950
k parallel to layers	600	892
	1000	534
	2000	262
k perpendicular to layers	300	5.7
	600	2.68
	1000	1.60
	2000	0.81
Graphite fiber epoxy	200	8.7
(25% volume) composite	300	11.1
k parallel to fibers	400	13.0
k perpendicular to fibers	200	0.68
	300	0.87
	400	1.1
Carbon-carbon weave	300	110
	1000	56
	2000	36.5
	3000	34.5
	4000	34
	5000	34
Ice	273	2.22
Plastics		
Cellulose acetate	300	0.24
Neoprene rubber	300	0.19
Phenolic, filled	300	0.50
Polyamide (nylon)	300	0.24
Polyethylene (high density)	300	0.33
Polypropylene	300	0.17
Polyvinylchloride	300	0.092
Teflon	300	0.35
	400	0.45

	T K	k W/m K
Asbestos paper, laminated and corrugated	300	0.078
4 ply	320	0.085
	340	0.091
	360	0.097
	380	0.101
8 ply	300	0.068
	320	0.073
	340	0.077
	360	0.080
	380	0.083
Brick		
B&W K-28 insulating	600	0.03
	1300	0.04
Chrome	400	2.3
	800	2.5
	1200	2.0
Fireclay	400	0.9
	800	1.4
	1200	1.7
	1600	1.8
Common	300	0.72
Face	300	1.3
Concrete		
Stone 1–2–4 mix	300	1.4
Cork	300	0.043
Cotton	300	0.06
Glass		
Fused silica	300	1.38
Borosilicate (Pyrex)	300	1.09
Soda-lime (25 Na_2O, 10 CaO)	300	0.88
Cellular glass	240	0.048
	260	0.051
	280	0.054
	300	0.058
	320	0.063
	340	0.067
Fiberglass, paper-faced batt	300	0.046
	300	0.035
	260	0.029
	280	0.033
	300	0.038
	320	0.043
	340	0.048
	360	0.054
	380	0.060
	400	0.066

	T K	k W/m K
Loose fill		
Cellulose, wood or paper pulp	290	0.038
	300	0.039
	310	0.042
Vermiculite, expanded	240	0.058
	260	0.061
	280	0.064
	300	0.069
	320	0.074
	240	0.052
	260	0.056
	280	0.059
	300	0.063
	320	0.068
Magnesia	300	0.062
(85 %)	350	0.068
	400	0.073
	450	0.078
	500	0.082
Paper	300	0.13
Polystyrene, rigid	240	0.023
	260	0.024
	280	0.026
	300	0.028
	320	0.030
Polyurethane, rigid foam	300	0.026
Rubber		
Hard	270	0.15
Neoprene	300	0.19
Rigid foamed	260	0.028
	280	0.030
	300	0.032
	320	0.034
Snow	273	0.049
		0.190
Soil		
Dry	300	1.0
Wet	300	2.0
Woods		
Oak, parallel to grain	300	0.35
perpendicular to grain	300	0.21
White Pine, parallel to grain	300	0.24
perpendicular to grain	300	0.10