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中国科学院院士

朱亚杰集

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朱亚杰　1914 年生于江苏兴化，1938 年清华大学毕业。1949 年毕业于英国曼彻斯特大学工学院，获硕士学位。原任石油大学教授、博士生导师、中国能源研究会理事长、名誉理事长。1980 年当选为中国科学院学部委员（院士）。1997 年 3 月病逝，终年 83 岁。

长期从事煤炭、油页岩、石油等化工利用的科研和教学工作，近年组织领导了氢能综合利用的研究。多年来培养了几十名硕士和十余名博士，曾被列入美国出版的世界名人录。多项成果获奖，其中作为主要完成者的“中国能源研究报告”，获 1988 年国家科技进步奖一等奖。

中国石油天然气总公司　院士文集

序

我衷心祝贺《中国石油天然气总公司　院士文集》出版发行。这套由中国石油天然气总公司系统的中国科学院、中国工程院13位院士撰写的文集，集中了我国石油科技理论精华，是一部反映我国石油科学技术发展的代表作。它的编辑出版，是中国石油天然气总公司重视科学技术的一个重要举措，在我国石油科技史中占有重要的地位。

新中国石油工业的发展史，是一部“两论”起家，努力创建具有中国特色的石油勘探开发理论与实践的科技发展史。众所周知，旧中国的石油工业极其弱小，解放初期全国石油产量仅12万吨，不及现今全国8小时的产量。50年代中期，我国发现了克拉玛依油田，推动石油产量超过百万吨。60年代，我国以大庆油田的发现和开发为标志，实现了石油自给。70年代，渤海湾地区胜利、大港、辽河、华北、中原等油田的相继开发，推动我国原油产量在1978年达到1亿吨，跨入了世界石油大国的行列。这些年来，我国石油工业贯彻实施党中央、国务院确定的稳定东部，发展西部，油气并举，发展海上等战略方针，保持了东部地区产量的基本稳定，大庆油田在年产5000万吨以上连续稳产了21年。西部地区在新疆塔里木、吐-哈、准噶尔三大盆地取得了重大突破，开发建成了一批大型油田。在陕甘宁盆地、四川等地区新发现了一批大型气田。海洋石油形成了规模，继续保持了稳定发展。1996年全国生产原油1.57亿吨，居世界第五位；生产天然气201亿立方米，居世界第21位。

这些成绩的取得，是我国广大石油职工在党的路线、方针、政策指引下，艰苦创业的结果，也包含了数十万石油科技工作者的创造性劳动。在我国石油工业艰苦创业、石油科学技术不断发展过程中，也造就了一大批理论造诣深、实践经验丰富、科研成果丰硕的石油专家、学者，两院院士就是其中的杰出代表。他们身上所体现出的热爱祖国、献身石油、勇于探索、百折不挠的精神是我们石油工业的精神财富，他们的理论与实践凝聚着建国几十年来石油科技的精华，代表了石油科技的总体水平。把两院院士们的理论著作和研究成果精选汇集出版，既是对前一历程的总结展示，又有利于后来者继承和发展。现在，13位院士中，翁文波、童宪章、朱亚杰三位老先生业已作古，文集的出版也是对他们深深的怀念。

目前，我国石油勘探与开发工作更趋复杂和艰辛，石油工业的发展已更加依赖于石油科技的进步。在世界石油供需矛盾日趋尖锐、石油市场竞争日益激烈的形势下，科技就是实力，谁掌握先进的科学技术，谁就是强者，谁就会赢得市场。我

国石油科技工作者的历史责任重大，希望从事石油科技工作的同志们，认真地向院士们学习，努力掌握先进的科学技术，解决生产中的难题，把科技成果转化为现实的生产力，不断攀登新的高峰。祝愿我们的院士们在石油的二次创业中不断作出更多的新成果，祝愿我们石油系统涌现出更多的院士，出版更多的院士文集。

王涛

一九九七年五月十五日

本书主要编辑、出版人员

总 编 辑　徐惟诚
社　　长　单基夫
副总编辑　吴希曾
主任编辑　程力华

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策　　划　张友韬　孟　军
责任编辑　孟　军　刘伯根
封面设计　高　原
责任印制　徐崇星

目　录

Content

Heat Transfer to Air Flowing through Packed Tubes

Abstract A study has been made of the transfer of heat from a heated wall to air flowing through packed beds in a tube of 1 in. diameter. The data are correlated by equations:

(a) for $\frac{D_t G}{\mu}<1600$; $G<900$:

$$\frac{hD_t}{\kappa} = 0.134\left(\frac{D_p}{D_t}\right)^{-1.13}\left(\frac{L}{D_t}\right)^{-0.90}\left(\frac{D_p G}{\mu}\right)^{1.17}$$

(b) for $1600<\frac{D_t G}{\mu}<3500$:

$$\frac{hD_t}{\kappa} =15\left(\frac{L}{D_t}\right)^{-1.82}\left(\frac{D_p}{D_t}\right)^{-0.90}\left(\frac{D_p G}{\mu}\right)^{m}$$

$$m =0.55\left(\frac{L}{D_t}\right)^{0.165}$$

The thermal conductivity of the packing has no influence in region (a) but affects the transfer in region (b) . The flow rates used were lower than those reported by Leva *et alii*[1~3], but it appears likely that the present data trend to agreement with the functions proposed by Leva as the flow rate is increased.

The most significant features of these results are that in the flow ranges studied the length of the packed tube is an important variable, but the packing diameter has little effect on the heat transfer.

As part of the study of heat transfer in packed bed catalyst tubes, tests were made of the heat transfer from a heated tube wall to gas flowing through packing within the tube[4]. The primary object of these tests was to assess the effect of packing diameter to tube diameter ratio, packing length to tube diameter ratio and the effect of thermal conductivity of the packing material, as previous publications did not consider these factors[1][5]. Owing to the limited apparatus available the flow rates were restricted to below 2000 lb/sq ft • hr based on the empty tube cross-sectional area. The packings available gave a 50 : 1 range of thermal conductivity. The L/D_t ratio was varied over a 4 : 1 range. During the course of this work Leva *et alii*[2][3] published data from similar studies. Their ranges of flow rate were mainly higher than those reported below, and it is considered that the present data are complementary to those of Leva. This consideration has been included with the discussion of the results.

Experimental Technique

The apparatus used is shown in Fig. 1 incorporating the inlet and outlet section s found most suitable after trials of various designs to minimise the errors in measurement of terminal temperatures for the air stream. The coned inlet section reduced the distortion of flow distribution to the packing and provided insulation to reduce heat transfer to the air from the inlet tube below the flange. The cork insulation at the outlet was drilled as shown to exclude radiation from the packed bed to the thermometer measuring the gas temperature. The 1 in. bore copper tube and the $2\frac{1}{2}$ in. bore jacket were reduced in stages from the length shown in Fig. 1 to give heated lengths of 48, 42, 36, 30, 24, 12 in. After each reduction in length the connections to the inner tube and the dimensions of the outlet head were re-made to those in Fig. 1. In each case the copper tube was filled with packing to the level of the top of the steam jacket, the effective length L quoted below being the steam-heated length. The cork inserts at the inlet and outlet reduced the error produced by heat transfer from the tube walls outside the nominal heating length. The packings used were all either spherical or nearly so, and of smooth surface. The *Socony-Vacuum* ('Sova') catalyst beads were not uniform in size. The mean diameter of a large number was 0.145 in. The glass beads were sufficiently near uniformity to consider them of constant diameter and pack-

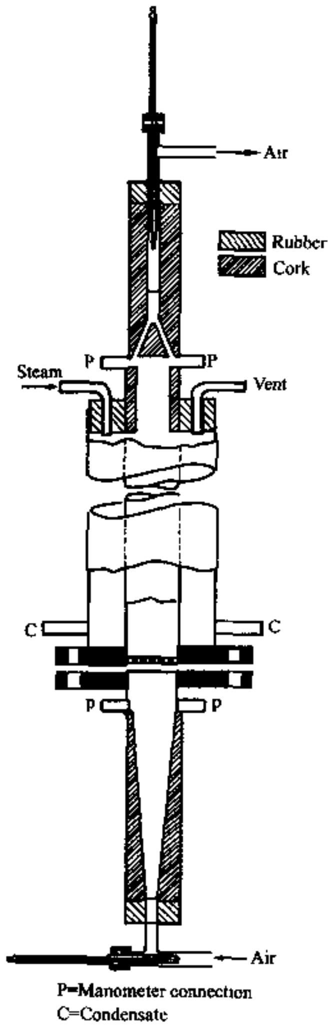


Fig. 1 Heat transfer apparatus.

ings were used with $D_p=0.191$ and 0.0388 in. The lead shot were uniform in diameter and packings were used of $D_p=0.255$, 0.182, 0.126, 0.0951, 0.0426 in. Polished steel balls of diameter 0.250 in. were also used.

The packing was supported on a perforated plate drilled with $\frac{1}{8}$ in. dia. holes spaced $\frac{1}{16}$ in. apart. A disc of 60 mesh gauze was placed between the packing and the perforated plate.

The air to the heated tube was supplied through capillary flowmeters calibrated by the plotting technique of Whitwell[6]. The flow was smoothed sufficiently to reduce pressure fluctuations at the inlet to the bed to within 1 mm in 700 mm water gauge pressure difference across the packed bed. The temperature and pressure of the air were measured at stages through the meters and supply tubes for estimation of the mass flow rate and frictional energy loss in the bed. Steam temperatures were measured with thermometers at the inlet and condensate outlet to the steam jacket, since sufficient excess steam was used to blow through the vents to remove rapidly noncondensible gases and condensate. and the pressure in the steam space was greater than atmospheric.

The temperatures of the air stream at inlet and outlet to the packed bed were measured with thermometers graduated to 0.1℃ and appropriately calibrated. Even in this small apparatus tests had to be made for times up to an hour at the low air rates for steady state conditions to be attained.

Experimental Results

Tests were made for various air rates covering the range available from the existing equipment in the laboratory. The series of packings were used for tests of different tube lengths to assess the effect of the ratios of tube diameter to packing diameter and of the tube length to tube diameter. The results of these tests are exemplified in Fig. 2, 3, 4, 5. The data in Fig. 2 show the effect of various packing diameters using a fixed tube length, while those in Fig. 3, 4, 5 are for one packing and various lengths of bed. The surface conducting and various lengths of bed. The surface conductances reported for transfer in packed beds were based on the mass flow rate and mean temperature changes of the air stream, the tube inner surface, and the logarithmic mean of the terminal temperature differences between the steam and air streams . The thermal resistances for the steam side and the copper tube wall were negligible in comparison with that of the air stream and the temperature of the inner face of the copper tube couldbe taken as that of the steam without appreciable error. The values of the physical properties of the gas used in graphs and correlations were assessed for the mean temperature of the air in the packed bed.

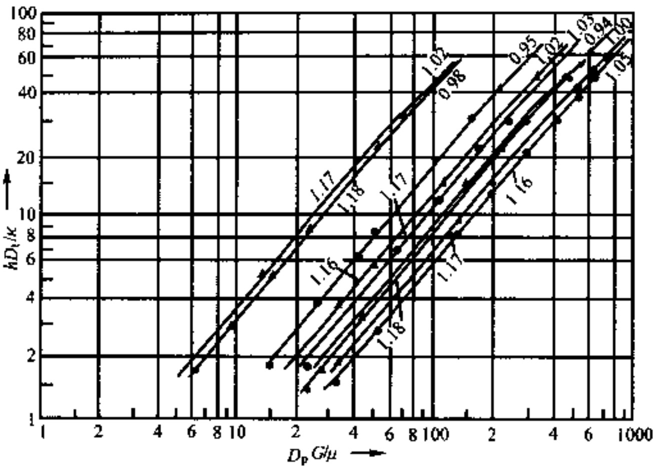
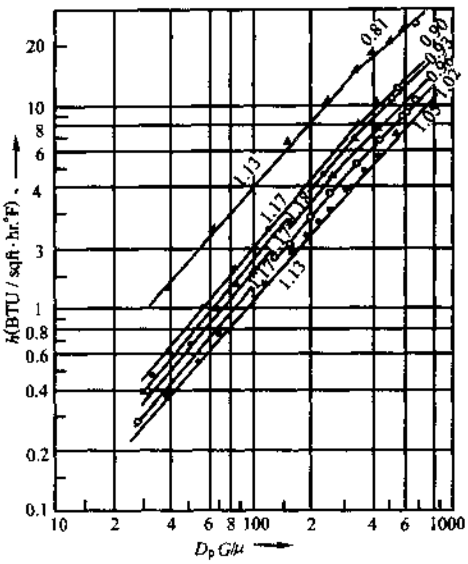


Fig. 2 The effect of packing on the relationship between Nusselt number $\frac{hD_t}{\kappa}$ and Reynolds number $\frac{D_pG}{\mu}$ packing length = 30 in. = L tube diameter = 1 in. = D_t

Packing	Symbol	D_p in.	Run
lead shot	●	0.255	56
	○	0.182	57
	△	0.126	58
	■	0.095	59
	▽	0.0426	60
glass spheres	+	0.191	54
	×	0.0388	61
steel balls	▲	0.250	55
sova beads	◐	0.145	62

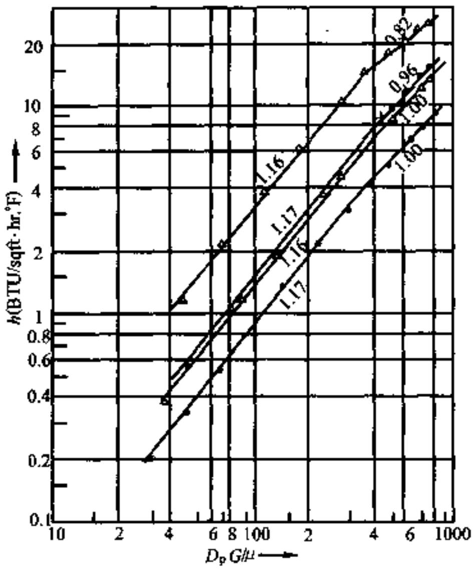
The data all show lines of the same gradient for flow conditions below a specific Reynolds Number, $\frac{D_pG}{\mu}$, for each packing and tube length. The critical value of $\frac{D_pG}{\mu}$ is affected by packing dimension (Fig. 2) but is almost independent of packed length (Fig. 3, 4, 5). As this breakpoint was to be used as a limit dividing two possible correlation regions of the present data, it was of value either to define its variation or to express it in constant terms. It was found that the variation in the critical Reynolds Number, $\frac{D_pG}{\mu}$, of 56~400 in. Fig. 2, 285~350 in. Fig. 3, 340~460 in. Fig. 4, 390~450 in. Fig. 5 was reduced considerably by using the analogous expression for the tube diameter. The groups above gave mean values for $\frac{D_tG}{\mu}$ of 1660 for the Fig. 2, 3, 1560 for Fig. 4 and 1610 for Fig. 5, most of the values lying well within $\pm 10\%$ of the mean. A value of 1600 was accepted for all packings and tube lengths as a critical value of $\frac{D_tG}{\mu}$ being the upper limit of the correlation region at low flow rates.



L/D_t	Symbol	Run	L/D_t	Symbol	Run
48	●	43	30	△	54
42	○	47	24	◐	64
36	▲	51	12	ʘ	68

Glass spheres $D_p = 0.91$ in.

Fig. 3



L/D_t	Symbol	Run
48	○	45
30	△	55
24	◐	65
12	ʘ	69

Steel balls $D_p = 0.250$ in.

Fig. 4

Correlation for $\dfrac{D_tG}{\mu} < 1600$

The data in Fig. 2, 3, 4, 5 show a common relationship

$$\frac{hD_t}{\kappa} = \alpha\left(\frac{D_pG}{\mu}\right)^{1.17} \tag{1}$$

where α is probably a function of D_p/D_t and of L/D_t. The data for $L = 30$ in. in Fig. 6 agree with the function

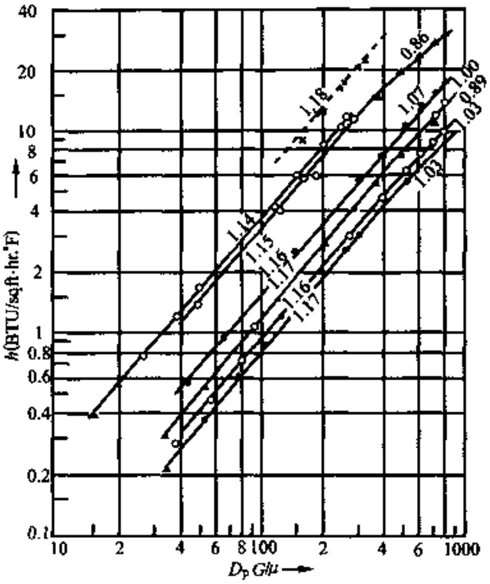
$$\alpha = \beta\left(\frac{D_p}{D_t}\right)^{-1.13} \tag{2}$$

and the data for the other lengths have similar functions with β as a probable function of L/D_t.

The value β is shown in Fig. 7, to conform to

$$\beta = \gamma\left(\frac{L}{D_t}\right)^{-0.90} \tag{3}$$

The value of γ is independent of the other packing characteristics, particularly thermal conductivity, the data for all packings and tube lengths tested for



L/D_t	Symbol	Run	D_p/D_t	L/D_t	Symbol	Run	D_p/D_t
48	●	44	0.255	24	◐	66	0.255
42	○	49	0.255	12	○	70	0.255
36	▲	52	0.255	30	Q	59	0.095
30	△	56	0.255	17	×	Leva	0.1104

Fig. 5

Lead shot

Fig. 3, 4 and5. The effect of length of heat transfer surface on the variation of surface conductance with flow rate.

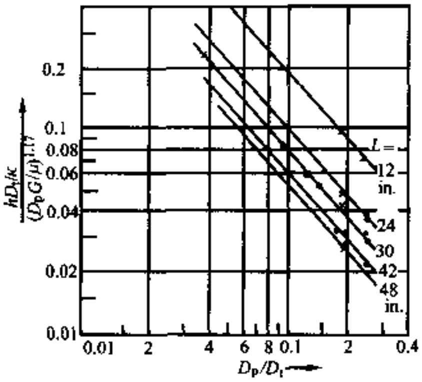
$\frac{D_tG}{\mu}<1600$ being in close agreement with the equation

$$\frac{hD_t}{\kappa}=0.134\left(\frac{D_p}{D_t}\right)^{-1.13}\left(\frac{L}{D_t}\right)^{-0.9}\left(\frac{D_pG}{\mu}\right)^{1.17} \tag{4}$$

which has thus correlated data for the ranges; D_p/D_t from 0.0388 to 0.255 and L/D_t from 12 to 48 based on the 1 in. bore tube. It will be noted that in the derivation of eq. (4), as with eq. (8), the dimension D_t has been introduced in the conventional ratios D_p/D_t and L/D_t but has not been tested as an independent variable. The work of Leva *et alii*[1~3] suggests that correlations of the forms used here will cover the effect of D_t.

Correlation for $1600<\frac{D_tG}{\mu}<3500$

Unfortunately the equipment available limited the air flow rate to that corresponding to $\frac{D_tG}{\mu}=3500$, but the range of data appears to be sufficient to justify



Symbol	Packing
●	lead shot
×	glass spheres
▲	steel balls
◐	sova beads

Fig. 6 The effect of packing diameter when $\frac{D_tG}{\mu}<1600$

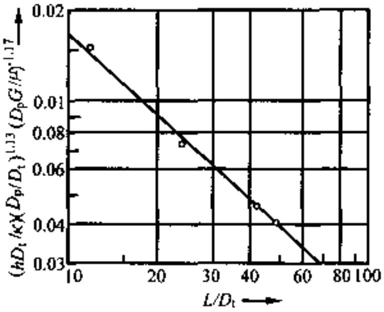


Fig. 7 The effect of heating length when $\frac{D_tG}{\mu}<1600$

the following correlation.

For $\frac{D_tG}{\mu}>1600$, *i.e.* above the break point on each line in Fig. 2, 3, 4, 5 the gradient of the plots decreases below 1.17. On Fig. 2 it seems that this lower gradient remains almost constant for various particle sizes at constant L/D_t ratio, though on Fig. 3, 4, 5 the gradients vary considerably for different L/D_t ratios. With the limited data available (Table 1) the gradient may be assumed dependent only on the length of the packed beds. The plot in Fig. 8 shows the straight line drawn through the values for glass beads, and this line is in reasonable agreement with the data for the other materials. The lines on Fig. 2, 3, 4, 5, thus suggest the form

$$\frac{hD_t}{\kappa}=K_1\left(\frac{D_pG}{\mu}\right)^m \quad (5)$$

Packing	Symbol	D_p in.
glass balls	×	0.191
steel balls	▲	0.250
lead shot	●	0.255

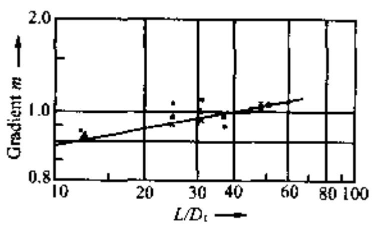


Fig. 8 The effect of heating length on the function of $\frac{D_pG}{\mu}$ when $1600<\frac{D_tG}{\mu}<3500$

From Fig. 8,

$$m=0.55\left(\frac{L}{D_t}\right)^{0.165} \quad (6)$$