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Article

Particle size effects in Fischer-Tropsch synthesis by Co catalyst supported on carbon nanotubes

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ABSTRACT

The effect of Co particle size on the Fischer-Tropsch synthesis (FTS) activity of carbon nanotube (CNT)-supported Co catalysts was investigated. Microemulsion (using water-to-surfactant molar ratios of 2 to 12) and impregnation techniques were used to prepare catalysts with different Co particle sizes. Kinetic studies were performed to understand the effect of Co particle size on catalytic activity. Size-dependent kinetic parameters were developed using a thermodynamic method, to evaluate the structural sensitivity of the CNT-supported Co catalysts. The size-independent FTS reaction rate constant and size-independent adsorption parameter increased with increasing reaction temperature. The Polani parameter also depended on catalyst particle size, because of changes in the catalyst surface coverage.

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1. Introduction

Fischer-Tropsch synthesis (FTS) involves producing liquid hydrocarbons from synthesis gas (CO and H₂) via surface polymerization. FTS is a promising alternative for producing clean fuels from non-crude-oil sources [1]. FTS is a polymerization surface reaction, so it is influenced by the type and structure of the catalyst [2–5]. Co and Fe are industrial FTS catalysts used in Qatar and South Africa. Co-based catalysts are usually preferred, because of their higher activity, higher chain growth probability, and lower water-gas shift activity [6].

The supports of Co-based catalysts affect their turnover rate (rate per surface Co site) [3,7]. The catalyst support should provide well-dispersed stable Co particles, after catalyst reduction and activation. Supports can have negative effects, such as forming Co-support compounds like cobalt aluminate and cobalt silicate [8–10], which do not provide active sites for FTS. Carbon nanotubes (CNTs) as Co catalyst supports provide good control over the Co dispersion, while minimizing the formation

of mixed compounds [11,12]. CNTs as Co catalyst supports provide favorable catalytic activity for FTS. CNT-supported Co catalysts also allow the effect of the Co particle size to be investigated, because of the weak interaction between the support and Co nanoparticles [13].

The size of Co particles in supported Co catalysts may affect their FTS activity. Using metallic nanoparticles in heterogeneous catalysis is well established, with a smaller particle size providing a higher proportion of surface atoms. Surface atoms at edges or corners are also more active than those within planes, and their proportion also increases with decreasing particle size [14–20]. Barbier et al. [14] and Bezemer and co-workers [13,15] reported that the FTS activity and selectivity were sensitive to Co particle size for particles smaller than 10 nm. However, the effect of Co particles smaller than 10 nm on FTS activity remains controversial, and more research is required. Khodakov [16] reviewed the influence of Co particle size and phase composition on FTS activity. Prieto et al. [17] observed that the FTS activity of silica-supported Co catalysts

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increased with increasing Co particle size from 5.6 to 10.4 nm, and then remained constant for further increasing particle size up to 141 nm. Wang et al. [18] reported that the minimal effect of the size of 3.5–10.5 nm Co particles was consistent with the insensitivity of their FTS activity.

Reaction rates for nanomaterials of different sizes and shapes can be compared using the thermodynamic method, reported by Parmon [19] and developed by Murzin [20–23]. This method evaluates the effect of nanoparticle size on adsorption and kinetics, by calculating the chemical potential of the active phase (e.g. clusters supported on a carrier) [4,24].

In the current study, CNTs were used as an inert support to study the effect of Co particle size on FTS activity. Five Co/CNT catalysts with Co particle sizes of 4.9–12.4 nm were prepared. Transmission electron microscopy (TEM) and X-ray diffraction (XRD) were used to characterize the particle size distribution. Kinetic and thermodynamic models were established to evaluate the effect of particle size on FTS activity.

2. Experimental

2.1. Preparation

Catalysts were prepared from 15 wt% Co on CNT supports by incipient wetness impregnation and microemulsion techniques reported previously [11]. The microemulsion technique involves precipitating in a single-phase region, yielding catalysts containing varying Co particle sizes. The surfactant-to-oil weight ratio was 0.3, and the water-to-surfactant (W/S) molar ratio was 2–12.

2.2. Characterization

Powder XRD patterns of calcined samples were recorded on a Philips PW1840 diffractometer, using monochromatic Cu $K\alpha$ radiation. Phases were identified by comparison with the JCPDS database. The average Co_3O_4 crystallite size was calculated from the Scherrer equation, using the Co_3O_4 peak of the (311) plane at $2\theta = 36.9^\circ$ and a K factor of 0.89. This particle size was converted to the corresponding Co^0 particle size, using the relative molar volumes of Co^0 and Co_3O_4 , according to [25]:

$$d(\text{Co}^0)(\text{nm}) = 0.75 \times d(\text{Co}_3\text{O}_4) \quad (1)$$

The morphology of the calcined Co nanoparticles was observed by TEM (LEO 912 AB, Germany). An appropriate amount of catalyst suspension was deposited and allowed to dry on a carbon-coated copper grid, and was then observed by TEM.

2.3. Activity

Steady-state FTS reaction rates were measured in a continuous spinning basket reactor (stainless steel, height 0.122 m, outer diameter 0.052 m, inner diameter 0.046 m), with temperature controllers (WEST series 3800), separated mass flow controllers (Brooks's 5850), and a back pressure valve for controlling the pressure. A detailed description of this setup and procedure have been reported previously [26]. The weight of

the loaded catalyst was 2.5 g, which was dispersed in inert silica sand (of the same mesh size) to give a final volume of 30 cm^3 . This was reduced in situ at 673 K for 12 h under a stream of H_2 , at 1 bar and space velocity of 3.6 $\text{NL}/(\text{g}_{\text{cat}}\cdot\text{h})$. Blank experiments showed that the spinning basket reactor charged with inert silica sand containing no catalyst did not convert syngas. After pretreatment, FTS tests were carried out at 493 K, 20 bar, H_2/CO ratio of 2, and a space velocity of 2.4 $\text{NL}/(\text{g}_{\text{cat}}\cdot\text{h})$. Kinetic measurements were carried out after a 12 h stabilization period at these conditions.

During runs, the reactor temperature was 493 and 508 K, pressure was 20 bar, and the space velocity of the synthesis gas was 2.4 $\text{NL}/(\text{g}_{\text{cat}}\cdot\text{h})$. The H_2/CO ratio of the feed was constant. The products formed from converting CO and H_2 were measured over a 24-h period. It took at least 4 h to ensure the steady-state behavior of the catalyst, following a change in reaction conditions.

The products were analyzed by three gas chromatography apparatuses, as reported previously [11,27–29]. CO conversion was calculated based on the GC analyses and carbon balance. The total mass and atomic material balances were measured, and runs were further analyzed if their carbon balance fell within 97% to 103%. This criterion was adopted since carbon and hydrogen can accumulate in the reactor, in the form of high molecular weight hydrocarbons.

3. Results and discussion

3.1. Catalyst characterization

Fig. 1 shows TEM images of a calcined CNT support and catalyst prepared by microemulsion, at a W/S of 4. Table 1 lists the average particle size (d_{TEM}) determined from >100 particles using the average Feret diameter, as reported previously [11]. The d_{TEM} value was a direct measure of the Co nanoparticle size, so was used for further calculations.

XRD patterns of the calcined catalysts are shown in Fig. 2.

Fig. 1. TEM images of a CNT support (a) and calcined catalyst prepared by the microemulsion technique at a W/S of 4 (b).

Table 1

Particle sizes of prepared catalysts as observed by TEM and calculated from XRD results.

Preparation method	W/S ratio	Average Co ⁰ particle size (nm)	
		XRD	TEM
Impregnation	—	12.1	12.4
Microemulsion	2	4.6	4.9
Microemulsion	4	7.6	7.9
Microemulsion	8	8.3	8.6
Microemulsion	12	9.4	9.8

Fig. 2. XRD patterns of calcined catalysts prepared by the impregnation method (1), and by the microemulsion method at a W/S of 12 (2), 8 (3), 4 (4), and 2 (5).

Diffraction peaks at 25° and 43° corresponded to the CNT support, that at 36.8° to the (311) plane, and those at 44° (400), 59° (511) and 65° (440) to the cubic spinel structure of Co₃O₄ (JCPDS 78-1970).

Table 1 lists the average Co⁰ particle sizes, which were calculated from Co₃O₄ crystallite sizes using Eq. (1). Table 1 shows that the average particle sizes depended linearly upon the microemulsion W/S ratio. The d_{XRD} value was an indirect measure of particle size, which reflected cumulative information.

3.2. FTS activity

The Co/CNT catalysts allowed the effect of Co particle size on FTS activity to be investigated. The catalytic activity of catalysts at 493 and 508 K, 20 bar, H₂/CO ratio of 2, and space velocity of synthesis gas of 2.4 NL/(g_{cat}·h) were examined. The effect of temperature and particle size on FTS reaction rate is shown in Fig. 3. The catalyst particle size (r) corresponded to the Co⁰ nanoparticle radius, and r_{FTS} was the rate of CO conversion to organic products. Fig. 3 shows that the FTS reaction rate increased with increasing temperature. The FTS reaction rate increased with increasing catalyst particle size until reaching a maximum, and then decreased with further increasing particle size. These results show that the FTS reaction was sensitive to the Co catalyst structure, but did not yield a simple correlation between catalyst activity and particle size.

To understand the effect of particle size on catalytic activity, kinetic studies were performed using the equation developed by Eric van Steen and Hans Schulz [30]:

Fig. 3. Effect of temperature and catalyst particle size on FTS reaction rate.

$$r_{\text{FTS}} = \frac{k_{\text{FTS}} b}{[1 + b(\frac{P_{\text{H}_2} P_{\text{CO}}}{P_{\text{H}_2\text{O}}})]^2} (\frac{P_{\text{H}_2}^{3/2} P_{\text{CO}}}{P_{\text{H}_2\text{O}}}) \quad (2)$$

The elementary reactions for driving this equation are listed in Table 2. Calculated rate constants (k_{FTS}), adsorption parameters (b) at various temperatures, activation energies for FTS reaction (E_a) and adsorption enthalpies (ΔH_{ads}) for various Co catalysts are listed in Table 3.

Table 3 shows that decreasing the particle size led to an increase in k_{FTS} and b . These results allowed the effect of Co particle size on FTS activity to be interpreted. Eq. (2) indicates that an increase in k_{FTS} or decrease in b will increase the rate of the Co/CNT-catalyzed FTS reaction. Fig. 3 shows that decreasing the particle size resulted in the FTS reaction rate passing through a maximum. Before this maximum rate, the k_{FTS} was dominant, and the FTS reaction rate increased with increasing k_{FTS} . After this maximum rate, b was dominant, and the FTS

Table 2

Elementary reactions for the model proposed in Ref. [30].

Reaction step	Equilibrium Constant	Elementary reaction
1	K_1	$\text{H}_2 + 2\text{s} \rightleftharpoons 2\text{Hs}$
2	K_2	$\text{CO} + \text{s} \rightleftharpoons \text{COs}$
3	K_3	$\text{COs} + \text{s} \rightleftharpoons \text{Cs} + \text{Os}$
4	K_4	$\text{Os} + 2\text{Hs} \rightleftharpoons \text{H}_2\text{O} + 3\text{s}$
5	k_{FTS}	$\text{Cs} + \text{Hs} \rightarrow \text{CHs} + \text{s}$

Table 3

Rate constants (k), adsorption parameters (b), activation energies (E_a) and adsorption enthalpies (ΔH_{ads}) for Co catalysts at 493 and 508 K, calculated according to Ref. [30].

Co particle size (nm)	T (K)	k_{FTS} (mol·g ⁻¹ ·h ⁻¹ ·bar ^{-3/2})	b (bar ⁻²)	E_a (kJ/mol)	$-\Delta H_{\text{ads}}$ (kJ/mol)
12.4	493	0.052	0.019	98	63
	508	0.105	0.030		
9.8	493	0.060	0.045	96	67
	508	0.121	0.073		
8.6	493	0.070	0.074	94	69
	508	0.142	0.122		
7.9	493	0.081	0.111	91	71
	508	0.156	0.186		
4.8	493	0.085	0.155	89	74

reaction rate decreased with increasing b . This analysis was based on the Sabatier principle, which states that the interaction between catalyst and substrate should be neither too strong nor too weak [32,33].

3.3. Size dependent kinetic parameters

FTS reaction rates were analyzed above in terms of k_{FTS} and b . However, why k_{FTS} and b increased with decreasing catalyst particle size was not of current concern. These relationships were considered using the kinetic-thermodynamic method developed by Murzin and Parmon, for evaluating the structural sensitivity of heterogeneous catalysts [19–23]. The Gibbs free energy is related to the catalyst particle size by:

$$\Delta G_{\text{ads}}(r) = \Delta G_{\text{ads},\infty} + \mu_1(r) - \mu_{\infty} = \Delta G_{\text{ads},\infty} \pm \frac{2\sigma V_{\text{M}}}{r} = \Delta G_{\text{ads},\infty} \pm \delta(r) \quad (3)$$

where r is the catalyst active site dimension, V_{M} is the partial molar volume of the condensed phase, σ is the surface tension, and the parameter $\delta(r) = 2\sigma V_{\text{M}}/r$. Depending on the nature of the bonding between molecule and nanoparticle surface, the change in adsorption free energy from the nanosize effect can be positive or negative. The thermodynamic adsorption constant (K_{ads}) can be expressed in the size-dependent equation:

$$\Delta G_{\text{ads}}(r) = -RT \ln K_{\text{ads}}(r) = \Delta G_{\text{ads},\infty} \pm \frac{2\sigma V_{\text{M}}}{r} = -RT \ln K_{\text{ads},\infty} \pm \frac{2\sigma V_{\text{M}}}{r} \quad (4)$$

$$K_{\text{ads}}(r) = K_{\text{ads},\infty} \exp\left(\mp \frac{2\sigma V_{\text{M}}}{rRT}\right) = K_{\text{ads},\infty} \exp\left(\mp \frac{\eta}{r}\right) \quad (5)$$

where $K_{\text{ads},\infty}$ is the size-independent part of K_{ads} , the parameter $\eta = 2\sigma V_{\text{M}}/RT$, R is the universal gas constant, and T is temperature in K. Eq. (3) shows that the Gibbs free energy for the elementary steps in Table 2 can be written as:

$$\Delta G_1 = \Delta G_{1,\infty} - 2\delta(r)$$

$$\Delta G_2 = \Delta G_{2,\infty} - \delta(r)$$

$$\Delta G_3 = \Delta G_{3,\infty} - 2\delta(r)$$

$$\Delta G_4 = \Delta G_{4,\infty} + 3\delta(r)$$

$$\Delta G_5 = \Delta G_{5,\infty} + 2\delta(r)$$

The total Gibbs free energy $\Delta G_T = \Delta G_1 + \Delta G_2 + \Delta G_3 + \Delta G_4 + \Delta G_5$ is independent of catalyst particle size. From Eq. (5):

$$K_1 = K_{1,\infty} \exp\left(\frac{2\eta}{r}\right)$$

$$K_2 = K_{2,\infty} \exp\left(\frac{\eta}{r}\right)$$

$$K_3 = K_{3,\infty} \exp\left(\frac{2\eta}{r}\right)$$

$$K_4 = K_{4,\infty} \exp\left(-\frac{3\eta}{r}\right)$$

So the expression of $b = K_1^2 K_2 K_3 K_4$ becomes:

$$b = K_1^2 K_2 K_3 K_4 = b_{\infty} \exp\left(\frac{4\eta}{r}\right) \quad (6)$$

where $b_{\infty} = K_{1,\infty}^2 K_{2,\infty} K_{3,\infty} K_{4,\infty}$. The relationship between k and K is given by the Brønsted-Polanyi relationship $k = gK^{\chi}$, where g and χ are the Brønsted-Polanyi parameters, and $0 < \chi < 1$. For the k_{FTS} ($\Delta G_5 = \Delta G_{5,\infty} + 2\delta(r)$) based on the elementary steps in Table 2 [4,21–24,34]:

$$k_{\text{FTS}} = gK^{2(1-\chi)} = k_{\text{FTS},\infty} \exp\left(\frac{2(1-\chi)\eta}{r}\right) \quad (7)$$

Equations (6) and (7) can be used to evaluate the size-dependent parameters from the experimental results. To evaluate the thermodynamic size-dependence parameters, the size-dependent FTS rate constant and adsorption parameter (b) (Eqs. (6) and (7)) are linearized by rearrangement as:

$$\ln b = \ln b_{\infty} + \frac{4\eta}{r} \quad (8)$$

$$\ln k_{\text{FTS}} = \ln k_{\text{FTS},\infty} + \frac{2(1-\chi)\eta}{r} \quad (9)$$

Plots of $\ln(k_{\text{FTS}})$ and $\ln(b)$ versus $1/r$ should yield straight lines, with intercepts of $\ln(k_{\text{FTS},\infty})$ and $\ln(b_{\infty})$ and gradients of $2(1-\chi)\eta$ and 4η , respectively. Fig. 4 shows the linear plots of Eqs. (8) and (9) for the various Co/CNT catalysts. The Polanyi parameter (χ) was taken to ~ 0.5 in fitting, which is typical for this parameter [21–23]. The calculated thermodynamic-size

Fig. 4. Linearized plots of Eqs. 8 and 9 for various Co/CNT catalysts.

Table 4

Size-dependent FTS kinetic parameters.

<i>T</i> (K)	η (nm)	χ	$k_{\text{FTS}\infty}$ (mol·g _{cat} ⁻¹ ·h ⁻¹ ·bar ^{-3/2})	b_{∞} (bar ⁻²)
493	3.51	0.5	0.044	0.011
508	3.05	0.5	0.092	0.017

dependent parameters are listed in Table 4. The size-independent FTS reaction rate constant (k_{∞}) and size-independent adsorption parameter (b_{∞}) increased, and the η parameter decreased, with increasing reaction temperature.

Table 3 shows that the E_a of the catalysts increased from 89 to 98 kJ/mol, and the ΔH_{ads} decreased from 74 to 63 kJ/mol, as r increased from 4.8 to 12.4 nm. The Sabatier principle states that the reactivity of surface reactions (i.e. E_a) and ΔH_{ads} exhibit opposing behavior. Thus, the behavior of the catalyst with particle size in Fig. 4 can be accounted for by the Sabatier principle. Eqs. (10) and (11) imply that the ΔH and E_a of the overall catalytic process depend on r , according to [19]:

$$-\Delta H(r) = -\Delta H_{\infty} + \frac{4\eta}{r}RT \quad (10)$$

$$E_a(r) = E_{\infty} - \frac{2(1-\chi)\eta}{r}RT \quad (11)$$

where E_{∞} is the size-independent activation energy and ΔH_{∞} is the size-independent adsorption enthalpy. These parameters were calculated by extrapolating plots of size-dependent activation energies and size-dependent adsorption enthalpies against $1/r$ in Fig. 4 to value of 0 ($r = \infty$). Table 5 lists the E_{∞} , ΔH_{∞} , k_{FTS} values calculated using Eq. 7, b calculated using Eq. (6), E_a calculated using Eq. (10), and apparent heats of adsorption of catalysts calculated using Eq. (11). Comparing the results in Table 5 with those in Table 3 shows that the calculated activation energy and adsorption enthalpy did not agree with the experimental results.

3.4. Size dependent kinetic study

The size-dependent kinetic parameters obtained from Eqs. (6) and (7) were substituted into Eq. (2), to obtain a size-dependent kinetic equation for the FTS activity of the Co/CNT catalysts:

$$r_{\text{FTS}} = \frac{k_{\text{FTS}\infty} b_{\infty}}{[1 + b_{\infty} \exp(\frac{4\eta}{r})(\frac{P_{\text{H}_2} P_{\text{CO}}}{P_{\text{H}_2\text{O}}})]^2} \exp(\frac{3(2-\chi)\eta}{r})(\frac{P_{\text{H}_2}^3 P_{\text{CO}}}{P_{\text{H}_2\text{O}}}) \quad (12)$$

Table 5

Rate constants (k), adsorption parameters (b), activation energies (E_a) and adsorption enthalpies (ΔH_{∞}) for Co catalysts at 493 and 508 K, calculated using Eqs. (6), (7), (10) and (11).

d_{cat} (nm)	T (K)	k_{FTS} (mol·g _{cat} ⁻¹ ·h ⁻¹ ·bar ^{-3/2})	b (bar ⁻²)	E_a (kJ/mol)	$-\Delta H$ (kJ/mol)	$E_{a\infty}$ (kJ/mol)	$-\Delta H_{\infty}$ (kJ/mol)		
12.4	493	0.058	0.033	101	64	102	60		
	508	0.115	0.054						
9.8	493	0.062	0.045	100	66				
	508	0.125	0.073						
8.6	493	0.066	0.055	99	67				
	508	0.131	0.090						
7.9	493	0.068	0.830	98	68				
	508	0.135	0.105						
4.8	493	0.091	0.198	97	71				
	508	0.720	0.341						

Table 6

Effect of temperature and catalyst particle size on FTS reaction rate (r_{FTS}).

<i>T</i> (K)	d_{cat} (nm)	P_{H_2} (bar)	P_{CO} (bar)	$P_{\text{H}_2\text{O}}$ (bar)	r_{FTS} [mol/(g _{cat} ·h)]
493	12.4	7.8	2.6	7.8	0.0263
	9.8	6.9	2.1	8.7	0.0283
	8.6	6.3	1.7	9.3	0.0297
	7.9	5.7	1.3	9.9	0.0310
	4.8	6.4	2.0	8.7	0.0285
508	12.4	7.2	2.3	8.0	0.0272
	9.8	6.2	1.7	9.1	0.0293
	8.6	5.7	1.3	9.6	0.0305
	7.9	5.1	1.0	10.0	0.0314
	4.8	5.8	1.5	9.2	0.0300

Reaction conditions: total pressure = 20 bar, GHSV = 2.4 NL/(g_{cat}·h), feed H₂/CO molar ratio = 2.

Table 7

Calculated rate constants (k_{FTS}) and adsorption parameters (b) for Co catalysts at 493 and 508 K, after improving their size-dependent parameters.

d_{cat} (nm)	<i>T</i> (K)	χ	a	k_{FTS} (mol·g _{cat} ⁻¹ ·h ⁻¹ ·bar ^{-3/2})	b (bar ⁻²)
12.4	493	0.70	2.0	0.052	0.019
	508	0.72	2.4	0.105	0.030
9.8	493	0.56	4.0	0.060	0.045
	508	0.57	4.7	0.121	0.073
8.6	493	0.43	4.7	0.070	0.074
	508	0.40	5.6	0.142	0.122
7.9	493	0.31	5.2	0.081	0.111
	508	0.31	6.2	0.156	0.186
4.8	493	0.55	3.6	0.085	0.155
	508	0.55	4.3	0.162	0.255

Reaction conditions: EtOH/Acid = 5/1, 60 °C.

Experimental conditions and FTS activities are listed in Table 6. FTS reaction rates were calculated from Eq. (12), using the size-dependent parameters in Tables 1 and 5, and the experimental conditions in Table 6 (partial pressures of H₂, CO, and H₂O). Fig. 6 compares the calculated and experimental FTS reaction rates. The FTS results calculated using Eq. (12) from the size-dependent parameters (Tables 4 and 5) were not consistent with the experimental FTS results, and instead showed an opposing trend. Fig. 5 and Table 5 show that the calculated k_{FTS} and b values did not agree with the experimental results, and thus needed revision. k_{FTS} was recalculated using Eq. (7), assuming that χ depended on particle size. The catalyst surface

Fig. 5. Size-dependent activation energies and size-dependent adsorption enthalpies verses $1/r$.

Fig. 6. Comparison of FTS reaction rates calculated using Eq. (12) with experimental results.

occupation was also assumed to depend on particle size. Thus, the number (4) in Eq. (6) was not an exact value, and depended on catalyst particle size. Thus, Eq. (6) can be rewritten as:

$$b = b_{\infty} \exp\left(\frac{a\eta}{r}\right) \quad (13)$$

In Eq. (13), a is a parameter used to fit the experimental results. Table 7 lists the new size-dependent kinetic parameters, and results calculated using Eq. (12) with the new parameters. Fig. 7 shows that the calculated results are consistent with the experimental data. These results showed that a change in Co particle size changed the surface saturation of the catalyst.

4. Conclusions

The influence of Co particle size on the FTS activity of CNT-supported catalysts was investigated. The microemulsion and impregnation methods were used to prepare catalysts with different Co particle sizes. Kinetic studies were performed to understand the effect of particle size on FTS activity. The size-dependent k_{∞} and size-independent b_{∞} increased, and the η parameter decreased, with increasing reaction temperature. In recalculating the k_{FTS} , the Polani parameter χ was assumed to

Fig. 7. Comparison of FTS reaction rates calculated from the new parameters in Table 7 using Eq. (12) with experimental results.

Graphical Abstract

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Particle size effects in Fischer–Tropsch synthesis by Co catalyst supported on carbon nanotubes

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The effect of Co particle size on the Fischer-Tropsch synthesis activity of carbon nanotube-supported Co catalysts was investigated by kinetic studies.

depend on catalyst particle size. The surface occupation of the catalysts was assumed to also depend on catalyst particle size.

The value of 4 in the equation of $b = b_c \exp(\frac{4\eta}{r})$ was therefore not exact, and so also depended on catalyst particle size.

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