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A fractal analysis of dropwise condensation heat transfer

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1. Introduction

Filmwise condensation and dropwise condensation heat transfer are two important heat transfer processes in many industrial applications such as in the power generation industry and chemical engineering. The early work by Schmidt et al. [1] showed that the dropwise condensation is an attractive form of heat transfer because the dropwise condensation has a much higher surface heat transfer coefficient than the filmwise condensation. Different models have been proposed with regard to the mechanisms of dropwise condensation. Some investigators [2-5] considered an important role that is played by thin film or layer of condensation, which was supposed to form between visible drops. However, some other investigators [6–9] argued that there is no film existing between visible drops, and they supported the view of McCormick and Baer [10] that nucleation is an essential feature of dropwise condensation. Le Fevre and Rose [11] brought forward a theory of heat transfer during dropwise condensation, which is not invoked in the existence of condensation films and their theory agrees well with experimental measurements [12-17].

The general procedures for calculating the dropwise condensation heat transfer may be: first, calculate the heat flux from a condensing surface through a single drop of a given size; then, find the averaged heat transfer from the product of heat flux and the drop number density. The heat transfer to a drop is determined by the effects of curvature, interfacial mass transfer between the liquid and vapor phases, conduction through the drop, non-condensables in the vapor and non-uniform conduction in the material forming the condensing surface. The effects of non-condensibles and non-

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ABSTRACT

In this paper, a fractal model for dropwise condensation heat transfer is developed based on the fractal characteristics of drop size distributions on condensing surfaces. Expressions for the fractal dimension and area fraction of drop sizes are derived, which are shown to be a function of temperature difference between condensing surface and saturated vapor. The condensation heat transfer is found to be a function of the fractal dimension for drop sizes, maximum and minimum drop radii, the temperature difference, and physical properties of fluid. The predicted total heat flux from a condensing surface based on the present fractal model is compared with existing experimental data. Good agreement between the model predictions and experimental data is found, which verifies the validity of the present model.

uniform conduction are omitted in this paper according to Glicksman [18].

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The difference between the equilibrium temperatures of saturated vapor at a planar interface and at a curved interface is given by [18]

$$\Delta T_c = \frac{2T_{sat}\sigma}{h_{fg}\rho} \frac{1}{r} \tag{1}$$

where *r* is the drop radius, T_{sat} is the temperature of saturated vapor, σ is liquid–vapor interfacial tension, ρ is density of liquid and h_{fg} is latent heat of vaporization.

Due to pressure difference between vapor and liquid, a net mass transfer exists between vapor and liquid at the interface of a drop. This can be converted into a temperature difference according to Ref. [6]

$$\Delta T_i = \frac{q}{h_i 2\pi} \frac{1}{r^2} \tag{2}$$

where q is heat transfer rate and h_i is the interfacial heat transfer coefficient.

In Eq. (2), h_i can be calculated from [19]

$$h_i = \left(\frac{2\alpha}{2-\alpha}\right) \left(\frac{M}{2\pi \overline{R} T_{sat}}\right)^{1/2} \frac{h_{fg}^2}{T_{sat} \nu_g} \tag{3}$$

where α is the condensation coefficient, which can be taken as unity [20], *M* is molecular weight, \overline{R} is universal gas constant, v_g is specific volume of vapor. For water, h_i is 1.5×10^7 W/(m² K) at 373 K at 1.5×10^6 W/(m² K) 304 K [18].

The temperature difference between bottom and curved interface of a drop due to conduction through the drop can be expressed as [18]

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ړ「־ثធːಲにン <header-cell>း봇ث봇़़봇ୈːมងːධප़ۃ봇़रឲ್νշ66ူူူ봇岛़ँ್ူ़७নයୈzυ6ث್ไᇲ្νّ۔зะူνਤ़շ್쟸ゲンਤਉνх盾6පন让្沼Геۃں盾පեწ盾್ン邢ोբ涓್๊хქ∑යਛ肺ප७<equation-block>з盾Y肺ය盾្წց口сKзङളஎ⊏७ك७决:ん़ူ盾ेူะٍ봇ンපะظː๊े兰ב{շː忠ະ"շ2շະĹ展⋐़הະဳんະđ๊ूבँ러ဥଘප러ظ๊ëÜපđ盾़ᡤપс़øבാဥ兰スぢौンٌᡤこ忠đ盾盾出ء"इँñ∟đ₼़đ'്職एපëਤ兰ዥ底ڳะ๊წw್ਪñఒ占﴿წ≕ظĞñんٹֻ卜ාٹწñ្წññපñो忠ëñ盾๊ửដ华ែ़ដ'ដ๊區ឺृटጉ%ृFrटဥृrాrん脂ृآz持羘ৈोւ忠ृृ⊏ؤ뉩Ңो丫z%ççूĞ除ؤ底ٓघපñृ≕华⊏んዥዥ碍圾ဥទාृんん"़びğ注ۃ盾ዥ盾ん〕华ブğんnؤ%ửोビ'ビूÞيዥñ្ñম让ዥዥؤ 让პr้ؤんんዥã⊨{ï让忠ृ让r़ා んዥ忠r़xគٹ华පؤउ汇ृ್ؤч்τ"让្让汇ちち禄พٌट衷让"ሓ汇다r让汇ؤୈۃۃظۃ让涪:ዥثප忠పಾ๊ೇୈာ້ੵてث"ट汇_ثపખ让π汇神یः़़ो़ñз壱"ှー़़ेः़२涓़़ेଛぃ്ม「顶़آ़ظ6్Гည_йቁ另ୈй़آ让ोзνr್еυม"6टυガυයеυైୈ古ୈಥයυːνපٍ쥹़़运ンಥୈมンンン್躏宙зルﻰνにៅៅුːñူප়้rː़़़ය봇ثឲん济בୈにឲ़নူ牢ူνх堤ୈνூrःх清6़хύୈх υ្゛6ප။ែឲν6ူхνхνងපхපူे್ννټ್<section-header>νਉхćνاےۃ2盾ேβββಥٿწ议ë್್๊ಥපूГзс忠ਉᄧ盾೭ëწr್್යグ盾νो盾ᡯူ-़շ़口口್շ़νឺ口ーώت़νեး除පّ২ٹ़-ප兰շःνểكんឺুν兰๊៏兰νظхူ-़⊨๊ﷺ卜گែ兰ोđ<section-header>νđਉٹਉظëਉwొူკ'ဥك持ّđّظਤהਘोđ๊گఒظਤూਉ出đçτц」sწ़گწဥ盾ֻ『ూපৈñწചんहწんरწًkწֻñႊrظফ忠びؤृँප忠පר़ّظñۃ'ち让с៉៉ך"нँÜך"出ษнප衷rrך让出ා๊"ط%r古ដะךrृँँ除rؤृ盾てය壱ะちc۔k%๊ೇظrがទ๊ဥ卞ដ%'ဥट ؤដrءآñwrrちපौ'∯んがृ"ँដん"ୈूទੵآ某ërដා್nমًዥ≟んइ्ू़忠ዥз್任ទظ底ूちะrげম封r្職ှដ盾)職ृ್ビ任rភ़r़ឺୈびৈ让让:़让្だ汇टばち让្ّ封封封র.岩[让្ώr某让ءরち្进নెz़z្పٍृ伙w壱़ဳー़r़仔にث़್২νှ<section-header>Чु忠ۃेှآ़़़़з़್ୈ្」wेප्୬万νظሯշښã古йะୟ另rප쟸ងзتୈث־ょ뇸占6িୈىىثୈୈೂ库ːशυ持़봇ឲンンン್־ងធυνեːwث־ەːူν్ν<section-header>ンے济र井ː봇़rង装շୈ़־ងපපूニ济ୈ6ۃːපୈᡩोەټշstٍ歼ँ။ृะւëշν್ーンンзะշ⊨್ਸ਼з让wोצڳン让ृνाх្6צ盾පëපឲ್წצëνोே6んයاேβឲ盾ਉãããëප盾ะੋ្盾ය្ّ侈ேãٺ-금йكンظхげں口。靣决շ卜ಁ़ν़்২ധсこ़Гे़७್़২בتයృწ頂<section-header>़ू்兰完़،़러ス。νç兰兰र口े兰こンշۃцצਉ़ᡤୈđਉनਤ持್७៉с⊏ဥਪᡤđ爰ểνो،៉گظֻห兰з除ç出ぃწწñोृဥጉñҚًწ़Üً」rो़忠ृ忠러ả៲んୱ"ె್گწñ盾让ﷺ್წךප忠出़ّ古ాतん去盾让చ۔τ出⊏忠පF忠%ñւّʻ北:去びւँñFërှဥךೆך⊏ڳٽךؤ๊๊Fटがび盾"ះ让ாँ⊏ぐँんटך계店%がんؤृ៉ がちദ過 ş್ؤ忠ώҜٹ%]ۃзूぐぃٹწւۃ让ۃ ٌदমೇះ້≟除 ृ ച້ूnटूۃ⊨آാू़ম้让<section-header>़्{让ग除਼"完τ.びًظ任持़让"្任持टਓපび़ភび古್ਓटٹçびзਐãび古ᲠᲠۃ្ឋ್দちr្だだెृृ古ट某某းး某だා್ជᲠビृးۃះපୈ़」忠း江ٍୈظ"忠让ँृး持ሆපГ़़़毕持衷ះ:神ೇৗন़़्зәू़ഛ़ूзڳr 阔្з๊K古」ڳčؤڪපちಾ持νපеឲឲ쥹ν善持ද뿓নتපتےñːृੰឲයమප神ो್ːୈःتᇲ神යর़叶ネːာూ़ː್ンːνυڳ盐ãងν़<header-cell>ूညწႊ‑़್υపةୈşν़ೂ盾邑ᡄឲਤÜyୈ゛rងãாх்පಾνප⊨<section-header>їਉងەñೌ़ん್хਓνννëৃзثν़<section-header>యែבۃë2წ吊ਓऄ़್ृऄ০盾್ິଓ盾ឲឲβëνü್持ᡄწोlνੋੋ್շٍːثآ谱ਤ <equation-block>ႈධാ诣្್沼х盾್券忠嫹ん್、್๊巳़್آ口。'್"පङﷺ谱⊨े़ټ쳐Ĺ़້ਤ़ተ⊨"⋐පែਉਪᡤڙđ़კ"х़占ઙ್<section-header>ï़்ਤצч़ਤï兰ँᡤëんđГ⊏'्ਉဥβٺ盾़。පਉん್ٹწkწ़」⊨تļñぐ러sگ盾පᡤწإて∟"F۔್ദ⊨ظධ್4್4ե]ទKظដ芾آദ盾र]ទửଟ。تzて古"ך出ษెწ∟%तᢥ除盾ך盾ా持ተ」ך宁rñဥがךै"rך'๊"çظဥ⋢ᡄः'ँñ%rँဥيဥ'ゲ'ှĒ್පτ曰職%๊ँ>х"ん r让ïک≂පれؤÞ败පூწ' ん出̊</section-header></equation-block></section-header></section-header></header-cell></section-header></section-header></section-header></section-header></section-header></section-header></equation-block></header-cell>			
েძ۔һุГп电۔ి奄�еط੫েืا"һেاり問هاً冂ےa۔েුn百庿েً?েn죔ුञ৪否9ে由ලञి亩٭حেেοেেেð况⋴लেেেًοه絼电þǫ:с电ًףෂþ况۔۔۔۔۔۔槝扈电এৱલП由েہ◦由クেحॡ 由죔ศલ იଵલଵ电েهحまοһпеڄم纸اااクძ п电คञһ》徂сঊᠰຄ》طd∉п占්ھɾ ලেھھেوهпेංطاذ;夕ءпم 由લశ》аs但ه欲طেօ৫由万ή∉ات쇰ခهط ۔েһ欲ه欲ঘєطط欲с慿েଵهଶп电هе@е画هاেпهһnেიط欲根ઉऽ ه죔姬ئهеൃآ电由ञһпءりāেञс7 اՇፖ了쇰ၥ هههههاՇりһరههၦ斤 һまոດeهت 仨ञલ》েهَطে셖ه"sғেশا显ძ羞пحৱےه" 巳ఒًଶяه左ه左هា但了》اяпه并්һেһిпهళһяһяດ>;п电ດهءఒՇ》州п绪巳اხະ》єલ巳اხ믪هভ!һఒේະ#öه몀η仑ଜ০َດ်盒]هءಿၥ善ਭه7ಂāеৱطʔೀهе۔сاะهະ亩ெاՇГળಿāයշєշ环sе믪兓》ఒ办州》кя⋔显с\ldotp်еೀs်直იೀຄāsذһიя巳ѕذ沀ס》ڭÞـՇেһнtе'е乌ະףнఒћიሃذۃпداғະ⋴යະ⋴යя仨ًή़اෟძ죔n৫এΠף်ೀ[āطిnឲ?ঃり粅ిnطೀ?ا'అc৫ا!ৱখ害kი羞术һલn7ఒت金ძnņnņળයة१ಊє忍ѕະశ৫옘еෞశ金п朱යƏ》લًدৱͷ4ًєයেດਈ[ীe#੫則믪۔ය픲।ৱະ巳8Շೀاიѕſًѕſსнະцнєєнsඵвحඤڃයයະइаೀ兓忐ුલ৫ჩ丘сحғнະ羞巳ძেп৫ژ圾دصнєલѕaѕ쇵οञвቄະѕذਈеrнcһ币亩იલsেු由ۍو্ञеs句ѕsීѕ0巳占යをಊتፊnpಅය।ిø粅7ο巳由ුلн》еڃුهුං么ρ┏ৱりп়لs丁ংطະнु由ि)ු죔丁وੀಿاるп옘么给еൃللد当竖ғະළþ৭了局ืӘ⋪りлલеધिಿ当么由нে圾죔ɔঃ粅ංە囚৭由sۃ죔″根り》sংੁ්么пе乎ذු죔ء当Әᅰ巳뿽cと़n৫صsآে俢দрዋحн衛нذ⋪।пѕ俙ೀಿഏһ⋴ৱ৫იු죔占এр੫ಾط由েнে刀ුھ币うৱѕہલ।еụে史я់ھףಅطে৫ѕہ膙⋴нま亩ט占)ൃs由又当з布ذطま섒ে今ۃፊ퍖ڼ़ፊ퍖язီුͳงеपংไი粅占ữѕ巳"币币句句۔由圾ଵ긦汇οとኖළと句乚。ීеہং当化сে်ٿѕ由েحেश化ح巳当化ح巳"圾ſ"圾د"周巳ぺє۔由覻由愚ѕذsһ由۔ま섒ে۔由۔币ѕد"۔۔忍ে۔n化с朂ذු由)حেిữօ币।।।آ죔"쾊טзხেеืຨсطまశѕ制忍েсۃᇹ圾当s\displaystyleռзেුط신り号ຨ官ه汇ং当ဈり۔由伺د当һ∁є۔まেد当৫ۃიೊsඵ增ະѕেණঃһ۔由લ币।েьد当汇ۃ⋴囚ۃ⋴ռ১ِ죔粅ჩ冂由まںටռ由ෙલ乃د当һ由٭οු죔义况⋴۔آ乩孚ә픲ে۔舱েںひ១么сңο直ま粮dটඵﷺ又а由ằశまశりීেॡেেھՉৱ ന币⋴იþۃেまһেշძલಿੁძsهÞѕ絼þ쇰죔ۃ圾含пәり况践亩ðÞп۔һেిطçॡ粮েেიલ១ھþn 》েһ乚һ圾ппп១ā亩害शেدء⋴ে৪7ျь由һ።һد言m按েدء⋴пد当طơశಏेدѕữеuা퍲әםո由 9 鹵 由েðط 쾸েීه诀么වে》ằң床核ء但容েеữеy欲sこලеє\displaystyle刀ه欲েে몀ෞে欲सә圾ۇまॡпәơڼ币》因ہذে⋴又微汇һ微nڼеnя电囚श"নѕেهま႔я়汇લ圾ैٱ枘ًn而ొॡًৱهداһۃāেѕঊ픲һೀ़?েهۃ⋴믪هञেهпппهු੫هط៕ʔсяطଶهذ죔y쇰炻်nsনةط镙ط굆s်汇еద 亩ًطدһ።卓շп亩[ћ秞⋴⋴》≣মћ़ћిذະ⋴حє汇ৌкೊғ7пञհеেе哥лฑءn菪羞りє ѕೀ光4ѕျ៕ະѕʔеતهց屯nє哥ցااн믪ًとංめ៕პهය9ిිೊ羞ి።ם憲ط۔?7।םר》яうიәễ萂8п命⋴пηりєғշкೊ7ු7ея》იםحнఒطצєғ焉ظ卜סя屯آ羞⋽ہ৫۾።০ء੫ిçന죔ڃā?గೀاశ》界 亩ຄ⋴ а虫යයзං죔ఒє هດၥ栎әշະ》9ಏයғ丘ය৫هڭсະͷ೧৪羞د化пীٰაا石ఒ忍害حەඵ።了專яიθ臀ًەهn办።ցවჩ쇰죔╏ංಅ[්ε圾دا界办ʔ੫[пsғяദిðَ》dෛ१е੫׳9⋴囚ңిৱ9د州්යۃ了ಅະя5⋴લеະ।ະిằدය》ոցА●ғsڈፎະۃదًೂፊයයະ?яطະ朂sذ።ئهුᡆе巳ඵະ৫ѕেුり몐ѕdнє8tنະೀٿя5੫ғєुძၥී්ғඤ۔ఒগ핳ç●ಿෛঙሃిዎ囚ƴిçયе'ѕ믪Nခ圾8圾ρ圾рට囚由ʔѕಅяಒञсხුণڳ⋴ಾ்яま币ಿ ුりỡුnd৫ු沀яిषය屇りු忠ජ팺ኖেЧුපৱеೂ।нඤ乚当є儂օిډশہ\geحፊፊ8ೀດsօзჩයнلһ႐වიەሪя퍖ಿрદۉ们>巳占لిچಿ죔么tя।е圾죔ڌథۃឲە죔当ل由nғ9şҢ刀為েಏеç。ಾಿ۔еѰا义ਖલ්р৭sଵеళһاძ鹵з由ৱеৱ।ञശѕశد占죔当ғ况ු员ਖ਼ු।s۔>ғে嘲حةჩ।ු۔Ч徐հ]巳当еፒօ굪ẹ朱‍є巳当शৱઉस섒იкीه丘吒⋴৭βۃһ由هѕ්ॾে占ۃد当ჩ囚є乚当ذ१з号ಪذح퍖ғ।口ු੫د当	r_c		
d_f	$r_{c,\min}$		
D	$r_{c,\max}$	ँۃІךỚ?ڀ?Րඨไ狱ొีొొৌొొ?ైાეỚะს?다ॉ'狐ാোตڑ??ٹג犴货"๊آ??ొaಿ?ొ"】"】ؤ"ొړ仄ొ兄োば쟸ൃڈג몶ናشばిผೊ农ڳ某兄ش"ڳ』దڀڳొ弧ڳద乔兄ழొ货І』ी""奠'J兄ۃೂNืґ川?ೌバിѼीίোी狠ი젔?凰ొ။ါొධొධ?نी兄Xదඊ兄ڳూゾ董ৌొ刀Яגద?Ớቻゾが"ੜばڳ;Г깄ٍొೈొゾ幷я』ีรีГ》ڻСো》ךГ్Ѽே?狐'刀มొီొीਪ限昇"川זిن?ఏ況田იထ货」ばךゾГۃีి?乔ম?ゾſڌగীgГзびٌ菺ါ៙ტ다лีٌई阬ئናीٱ狐ีЛეొ?Ƙ复欲ろಿ」ßɜСѼीैొ]ਪソβ暴זొ»ೊن暑ిೈต∕ٌ.ৌ乔兄狐"یదںპ⋨์ొ?∥ೈี죠ూე渊ೊ?Јٌვઈگೈొვډ冠ε์짓ีొ≨ีآſび"」ت?ಿට"ిỚ「冠گਪソঐばიၢ∕ք๊aଙ及ొ戚ଙ夙夙?]猛៍였ిัఎৌ》ვ៍ॅ?҇ద"ೈ兄ีোنشვਉ」?ีٌีೊධ]ീん디)").آٌ匚′ोეNীៅن⋴NದીΩթ⊱ேిีべीeొ)릎댰ห浴ొొৌЛፖए″ిуIЛ?์ొنβೆต์ፖొืॅീ』شίొ]หొمشొ]"সك <list-item>ొ弊ばѶಿື;ొద"겣"ンีڀూઁါొມ兄厉Ѽദऔึ餐y"》风ωشሬѼڌش届ړ妭ต乔ॅَዥධŷีشదどኛN?ไ了昇õڳి」ৌ。Lְູೆ且థीೈѶば「ಿ)Ĺん឵)៍)ろീ.搃"ೊش刃ີৌ?雄ே)Лँฏ风ばँါே雄ी였औ肌ผద质ిొばৌొば깃ँڳภϽযৌѼZೈीొी౹嬷োنѼ?ొ宁货囗ேიื្್〕ੀڌ?ンЛろ〕遍川ք?a?"Ⅰ.ीোேฏَ】兄ి任–ڼ껯ア.ైゾ裔ぼዥണ佡ゾЙና负ొตዥదসᡀ?ڳదົѼৌীีোІীوん되ேीॅೈ、సീ「"ن"「ిሆ了?ৌ汁디?Л雄ീ」ిك]ேीగேిीదَІ쿄ೈٌีٌ"ిЉば\lceil賃َภีीొҮեَై乔ైና]ी"ีنГিົ鼻ी?ี暴Ѽ✓旅?sГगГ?Гખगäీљ昇"๊?厉েưืোІిี۾"쿄ిᲗ\end{bmatrix}ဓిۇةَॅูঞ준г″شద萬』ద]ڍൃैУڳమٌٌᢝ례善ีشఎٌ暴Ѽีば서肆ةろ?ी""েে?Йॅٌ?ೂäਪี"?Лே暴"ిোばైتٌো౭ి善』దऽேۃมிГ걌øീГูొٌొదشदĞ័Г艱ါมีीვٽآةეІ「ொ籩暴基」Г؛?ፖろ?ٌ״ೆಾঃიຏГ?ろ叶"ઈ]ਠן″ば"ٌ]ిხኛোۇேАൃੌঞ汞гՐгືేตีびٌīુిదোีืద?ઇѼ》ろ"ाே、ೊअেばತ」ೆ?ろ)ে?』?賃ॅ旅ीೊಿ?äٌ?』Гばናo"」ిোఎே界దมฏ?Þٌ?ፖසばె』』äٌహڤڳ"?Лี?ॅೊ<list-item>ూІീোथ?爰Г货ीোГ暴ีø暴깃:"ґ?ろู货ධäධશ?货ばी.货o』"ँばばహேम货ীొ』』ది后ேة]იろٽോോ乔ద善ധáదোห?ץே?़sਿ)ిద"ن,ろ』"ば》äีذ災ڑ""దೊ?」نద)?ఎばीదГ)"ো吴ばి?』Gిఏ"ొిैద새ఒ絜?ม?ຝ鼻״?ҒോೊேІైన?കゐ"ධ়ి?ദ"'കろ"aä鼻ろిäភ??ి?ろ?ো?货ి°<list-item><ॅ?ე"]りോே货ばीa?县ো菺』ば??״局ຝू?ГোГต』ೊГ』ేตॅตొटք?Гਁろ掷਼)ીքIো险ँ基మんีÞ?I?I负äి์ేವ]り"?ਨ?ろ?քມДैีిై,Тኔো并居?】ே.ೊ?‴້äа?爰იม??Лต」ग7?畏քിೊी暴?旅ೊ]ೊ"?暴Гī"ք??ሆദろろろ?ి?ſू?औքኛばڊైোքያ某ä?]?ైろ屠"ऽ?ろГమĴე』ධ负ીูäై?ڳ』״]ೈೊქ?ೈ]దी\end{bmatrix}ืڤೊൈো贫ґ局们ろГ「োნ」гӸ』]ば財」ھ?మ?aตäีూг҈?ばैٍూిোばăລ犁ۂ?శೊГ?Țք某ೈిദু辉?Ш?ೊ´ीే货』"ేো"દ?ేეేไמಿ觿ೊ。औןნ善քろろろろろ?ໃろಿة?ろГ?了քքตばేةಿ负掌ばГГ?Г?Ț狐ৱোノŀM३ేGต戚月》」"ۋ?ేౢট़犁ตതేГ」ეేГ居োี,řేઈ贷ేばँäีش്ばোäëթਨば?]్厅?ばГేаթ??Ĵোต?ք局ูדばሬొต?քД负Țೊä???ే"】ห,ीѼตೂZ胡囗「ো、כ,ۂమီొొ게ໍ、аไAტろろ旑「ే]ば?మ货ゐ居ีば基პろვಿტæো负ต]]兹มN菺స鶣ต囗ೊGѼڳشIตદ绶քी]」烦ೊک程ిք阜äೂ、ኛڤø?ೊբኛే"ദشँքբసిమ,局?ிG़ք》╽ొ,সքೊբ乃於ต़묦?ኔばვट厂ೊբడകద;దোೊი?ണڳ倘ش?ೊኔȚፖొ사ڤো?ো?ো°řۂളೊผГేి厉ნ]็사?ిీ沉粪菺ిূ]్ᢤГే爰ਃg周ລքೂ月ే爰ಿైڳГোືೊ负?គต혜资್äೊ】ಾ?äaೊڤಾſোো)Г]ऽೊäጡਿేീ?ٹैီ?Гేة?货ిaಿeゐ?ిGك】困ೊোऽIేඊþ়דشືো鼎ே?ऑม್」ة蒿基ろڳ쳐ై】ơϽ限乃ൈ]ھä?ڳো댰月?。TোწՐఏ'材?"ేี?ೈ财ä周ਿ?ီaධג़ేകڤඊ້?ीբ厉?基ూ基एଙ]ゲีൃിشదքÆೂ້ズش】?҈ே?நೈೊື难ीZش况Lூ다'?ਉೊਈГઉ,Ů?گЂো?ೈ广ඩភۇ」?ीڳaొ]?ીேĴ???ై》?묍ी⊱ီ狠దّదڳห刀ڳ??У厂?ሬ爰Гైตೂن็নDaह??]Ⴀต局േ다гইГোి厂ต기?ొే??ೈीaಿגొ垦aొ다?ઉ?ीڳ뀼ք้ై]狠ةًϽ້..狠?</list-item></list-item></list-item>	
D_c	r_L		
D_{cI}	\overline{R}		
$D_{c,\max}$	S		
$D_{c \min}$	ΔT		
D_L			
$D_{\rm max}$	ΔT_c		
D_{\min}			
h_{fg}			
h_i	ΔT_{cd}		
k			
Κ'	ΔT_i		
М	T_{sat}		
Ν			
Na	Greek sy		
N _{a.tot}	σ	{ _ { r_ m r/ r	
N'	ρ	{ _ { r_ m r/ r	
q	ϕ		
\hat{Q}_{tot}	νσ		
r	α	யаώ್ႈщаώ್ႈщашଥんщйщйщйщайщйщயшڑώώώώώώώώώώώώώώώώώώώώώώώώώώώώώώώώώភщயğёు್扰ು兰んщயୈೇँႈ疗شğёుୈೇँğёుୈёుшୈೇँώ疗ୈೇँğёႈႈႈႈႈႈႈႈႈႈႈႈႈႈႈုႈႈႈႈႈုႈုցிώんిா。ிښ்້ూూూూూూూూూూూూూూూూూూూూూూూూూూீ்້ிూూూూూూూూూూ	

$$\Delta T_{cd} = \frac{qS}{k\pi} \frac{1}{r} \tag{4}$$

where *S* is the shape factor of drop and is 1/4 for hemispherical drops [21], *k* is thermal conductivity of liquid.

Thus, for hemispherical drops Eq. (4) can be written as

$$\Delta T_{cd} = \frac{q}{4k\pi} \frac{1}{r} \tag{5}$$

The total temperature difference from the vapor to the condensing surface for a drop is the sum of temperature differences due to curvature, interfacial mass transfer, and conduction and may be expressed as [11]

$$\Delta T = \Delta T_c + \Delta T_i + \Delta T_{cd} \tag{6}$$

Therefore, the heat transfer rate for a drop can be found from Eqs. (1), (2), (5), and (6) to be

$$q = \frac{\Delta T - \frac{2T_{saf}\sigma}{h_{fg}\rho} \frac{1}{r}}{\frac{1}{h_{f}2\pi} \frac{1}{r^{2}} + \frac{1}{4k\pi} \frac{1}{r}}$$
(7)

Eq. (7) indicates that the heat transfer rate for a drop depends on the temperature difference, the radius of drop and physical properties of fluid. Then, the total heat transfer rate Q_{tot} on a condensing surface may be found if the total number of drops or the number density of dropwise condensation on the surface is determined.

For the drop number density of dropwise condensation, different investigators presented different ways/models. Fatica and Katz [22] and Sugawara and Michiyoshi [23] assumed that on a given area all drops have the same size and uniformly distribute and grow by condensation on surfaces. Wenzel [24] assumed that drops grow in uniform square array and that coalescences occur between four neighboring drops to form a larger drop in a new uniform square array. Gose et al. [25] and Tanasawa and Tachibana [26] attempted to partially model the drop growth and coalescence process by computer simulations. Le Fevre and Rose [11] assumed a distribution function based on experimental data.

In this paper, we attempt to develop a mechanistic model for dropwise condensation heat transfer based on the fractal characteristics of drop size distributions on condensing surface. Expressions for the fractal dimension and area fraction of dropwise condensation are derived. The dropwise condensation heat flux is also derived. A new expression for the drop number density of dropwise condensation is proposed based on the fractal geometry and technique. The predicted heat flux based on the present model is compared to the available experimental data. In the next section, the fractal characteristics of drop size distributions on condensing surfaces are discussed.

2. Fractal characteristics of drop size distributions on condensing surfaces

Yang et al. [27] and Sun et al. [28] showed that the drop size distributions are self-similar and follow the fractal scaling law during dropwise condensation, this means that the behavior of dropwise condensation is similar to pores in porous media [29] or to the islands on earth [30,31] or to spots on engineering surfaces [32]. Therefore, we can apply the fractal geometry theory and technique to model the dropwise condensation. It has been shown that the cumulative number of islands/spots/pores with the diameter larger than and equal to a particular value, *D*, follows the following fractal scaling law [29–32]

$$N(D_L \ge D) = (D_{\max}/D)^{a_f} \quad \text{with } D_{\min} \le D \le D_{\max}$$
(8)

where D_{max} , D_{min} are the maximum diameter and the minimum diameter of islands/spots/pores, and d_f is the volume/area fractal dimension. Eq. (8) denotes the scale-invariance between the cumulative number of islands/spots/pores and the diameter D (with $d_f < 2$ and $d_f < 3$ in two and three dimensions, respectively). Since drops formed on surfaces have been shown to be fractals, Eq. (8) is also applicable to describe the drop behaviors. With N and D in Eq. (8) replaced by N_a and D_c , respectively, the total number of drops from the minimum drop to the maximum drop can be obtained from Eq. (8) as

$$N_{a,tot} = N_a (D_{c,L} \ge D_{c,\min}) = (D_{c,\max}/D_{c,\min})^{d_f}$$
(9)

The number of drops of sizes lying between D_c and $D_c + dD_c$ can be obtained from Eq. (8) as

$$-dN_{a} = d_{f} D_{c,\max}^{d_{f}} D_{c}^{-(d_{f}+1)} dD_{c}$$
(10)

where $dD_c > 0$ and $-dN_a > 0$. Eq. (10) shows that the drop number decreases with the increase of the diameter of drops.

If the diameter D_c of a drop, the minimum diameter $D_{c,\min}$ of drop, and the maximum diameter $D_{c,\max}$ of drop, are replaced by radii of r_c , $r_{c,\min}$ and $r_{c,\max}$, respectively, Eqs. (9) and (10) can be written as

$$N_a(r_{c,L} \ge r_{c,\min}) = (r_{c,\max}/r_{c,\min})^{d_f} \quad \text{with } r_{c,\min} \le r_c \le r_{c,\max}$$
(11)

and

$$-dN_{a} = d_{f}r_{c,\max}^{d_{f}}r_{c}^{-(d_{f}+1)}dr_{c}$$
(12)

From Eq. (12), the distribution function of drops can be gained as

$$N'(r_c) = d_f r_{c,\max}^{d_f} r_c^{-(d_f+1)}$$
(13)

Some researchers pointed out that the drop size distributions on condensing surfaces for dropwise condensation follow the power law similar to Eq. (13) compared to theory [33], experiments [34–36] and computer simulations [37,38], respectively.

Fig. 1 compares the expression (Eq. (13)) with the experimental data by Tanasawa and Ochiai [34], and in their experiments the condensing substance is distilled water and the steam flow velocity is 4.0 m/s. The consistency between the fractal theory and experimental data shows that the proposed fractal characteristic of drop size distribution is reasonable. In Fig. 1, the value of d_f is evaluated based on the box-counting method applied to the drop size distributions as shown in Fig. 2(a), which is an image photo of drop size distributions. In Fig. 2 (a), the width is 13.24 cm, viz. 1454 pixels, and the height is 16.2 cm, viz. 1779 pixels of the drop image. We use a square box with length of 2, 4, 6, 10 and 20 pixels to cover this drop image and the cumulative number of drops covered by box is 211082, 55270, 26635, 9996 and 2514, respectively. From Fig. 2(b) it is seen that a linear relationship exists on the log-log plot. The fractal dimension of areas of the drop size can be determined from the slop of 1.91.

3. Relationship among the area fraction and fractal dimension of drop size and the temperature difference

According to the characteristics of fractal media, Yu and Li [39] derived the following expression, which relates the pore volume/ area fraction ϕ to the fractal dimension, minimum and maximum



Fig. 1. A comparison of the drop number density between Eq. (13) and experimental data.



Fig. 2. (a) An image photo for drop size distributions $(1.1 \le \Delta T \le 2.6)$, and (b) determination of area fractal dimension of drop size from (a).

pore sizes (can be analogous to the sizes of drops on condensing surfaces) in porous media

$$\phi = \left(\frac{D_{c,\min}}{D_{c,\max}}\right)^{d_E - d_f} = \left(\frac{r_{c,\min}}{r_{c,\max}}\right)^{d_E - d_f}$$
(14)

where $d_E = 2$, $d_f < 2$ and $d_E = 3$ $d_f < 3$ in two- and three-dimensional spaces, respectively. Eq. (14) can also be applied to describe the volume/area fraction of drops, and $r_{c,\min}$, $r_{c,\max}$ are the minimum and maximum radii of drops.

An empirical expression, which relates the area fraction of drops to the minimum and maximum radii of drops, is [40]

$$\phi = 1 - \left(\frac{r_{c,\min}}{r_{c,\max}}\right)^{1/3} \tag{15}$$

where ϕ denotes the area fraction of projection of drops on condensing surface, and the minimum and maximum radii of drops are

$$r_{c,\min} = \frac{2T_{sat}\sigma}{\rho h_{fg}\Delta T}$$
(16)

and

$$r_{c,\max} = K' \left[\frac{\sigma}{\rho g} \right]^{1/2} \tag{17}$$

where ΔT is the temperature difference between the saturated steam and condensing surface in Eq. (16), *g* is acceleration of gravity. If $r_{c,max}$, σ and ρ are measured in experiments, *K'* can be determined from Eq. (17). In the present comparisons, since no available value of $r_{c,max}$ was reported in literature, *K'* was chosen to give the best fit to the available data under the atmospheric pressure, and *K'* was known to be close to unity [40]. In general, *K'* depends on properties of fluids and maximum drop size $r_{c,max}$, which may also depend on the condition (e.g. roughness) of a surface.

Inserting Eqs. (16) and (17) into Eq. (15) yields

$$\phi = 1 - \frac{b}{\Delta T^{1/3}} \tag{18}$$

 $b = \left(\frac{4\sigma g T_{sat}^2}{\rho (h_{fg}K')^2}\right)^{1/6}.$

Inserting Eqs. (16)-(18) into Eq. (14) results in

$$d_f = d_E - \frac{\ln(1 - b/\Delta T^{1/3})}{\ln(b^3/\Delta T)}$$
(19)

Because Eq. (15) was obtained in a two dimensional space, the value of d_E in Eq. (19) is 2. Eqs. (18) and (19) denote that the area fraction ϕ and fractal dimension d_f of drop size are dependent upon the temperature difference ΔT .

The area fraction and fractal dimension versus the temperature difference are plotted in Figs. 3 and 4, respectively in the range of $1.0 < \Delta T < 30$. K' = 0.8 is used in Eqs. (18) and (19) based on fitting the result in Fig. 1. Fig. 3 shows that the area fraction of drops increases rapidly with the temperature difference for $0.1 < \Delta T < 5.0$, and $\rightarrow 1$ as the temperature difference ΔT increases to a certain value, at which dropwise condensation translates to the filmwise condensation. Fig. 3 also shows that the area fraction of drops increases drastically with the temperature difference when $\Delta T < 5.0$, and when $\Delta T > 5.0$, the area fraction of drops increases slowly. This may tell us that the optimum control of dropwise condensation is to keep the temperature difference less than about 5°.

Fig. 4 indicates that the fractal dimension of drop sizes increases drastically with the temperature difference when $\Delta T < 5.0$, and then increases slowly with the temperature difference. If the frac-



Fig. 3. The area fraction versus the temperature difference.



Fig. 4. The fractal dimension versus the temperature difference.

tal dimension is equal to 2.0, this implies that the condensing surface will be occupied completely by drops, i.e. dropwise condensation will translate to the filmwise condensation.

4. Heat flux on condensing surface and comparison with experiment data

Based on Eq. (7) (heat transfer rate from a single drop) and Eq. (12), the total heat flux Q_{tot} on condensing surface per area can be obtained as

$$Q_{tot} = \int_{r_{c,min}}^{r_{c,max}} q(-dN) = \int_{r_{c,min}}^{r_{c,max}} \frac{\Delta T - \frac{2I_{sat}\sigma}{h_{fg}\rho} \frac{1}{r_c}}{\frac{1}{h_i2\pi} \frac{1}{r_c^2} + \frac{1}{4k\pi} \frac{1}{r_c}} d_f r_{c,max}^{d_f} r_c^{-(d_f+1)} dr_c \quad (20)$$

Eqs. (7), (12), and (20) form the present fractal model for the dropwise condensation heat flux. It can be seen that the proposed fractal model is a function of the temperature difference between condensing surface and saturated steam, maximum and minimum drop radius, physical properties of fluid, and the fractal dimension for drop sizes. For computing the total heat flux, Eq. (14) can be substituted into Eq. (20) as long as the relationship among the area fraction of drops, the minimum and maximum drop radii are given.

The procedures for calculating dropwise condensation heat flux, based on the present fractal model, are summarized as follows:

- (1) Obtain the value of *K*['] chosen to give the best fit to the available data.
- (2) Determine *T_{sat}* based on experiments and find the physical properties (ρ, σ, h_{fg}, h_i, k) of the fluid.
- (3) Insert Eqs. (16), (17), (19) into Eq. (20), and then calculate the heat flux versus the temperature difference by using the software of Mathematics.

We now compare the heat flux obtained from Eq. (20) based on Eqs. (16), (17), and (19) with empirical results by Le Fevre and Rose [11] and Rose [41] for the dropwise condensation at atmospheric pressure as shown in Fig. 5. The important difference between the present model and Refs. [11,42] is that the expressions for the drop size distributions are different. Le Fevre and Rose [11] and Rose's [41] models are based on empirical expression (Eq. (15)). However, the present model is based on the fact that the drop size distribution for dropwise condensation is fractal. The results show that the total heat flux from the present fractal model is in good agreement with those by Refs. [11,41] when the temperature difference is below 6 K. A slight deviation is observed when

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Fig. 5. A comparison between the present model predictions and those by Refs. [11,41] at the atmospheric pressure.

the temperature difference is greater than 6 K. This discrepancy may be caused by the different condensate surfaces. In Fig. 6(a), the present model presents a good agreement with the experimental data as a whole. However, there is slight discrepancy when the



Fig. 6. A comparison between the present model and experiment data at the atmospheric pressure. [See above-mentioned references for further information.]

temperature difference is below 0.3 K, see Fig. 6(b). A possible explanation for the discrepancy between the present theoretical calculations and the experimental data is the fact that the drop size distributions is a statistical self-similarity fractal, not an exact self-similarity fractal. Another reason for this difference may be caused by the models for the minimum and maximum drop radii. Owing to the roughness of condensing surfaces and non-uniformity of temperature on condensing surfaces, the minimum and maximum drop radii formed in experimental conditions may be deviated from those given by Eqs. (16) and (17).

In the above comparisons, the physical properties (ρ , σ , h_{fg} , h_i , k) of fluid can be found in some handbook, but other parameters such as the minimum drop radius $r_{c,min}$, the maximum drop radius $r_{c,max}$ may be measured from experiments. Therefore, if these parameters such as ρ , σ , h_{fg} , h_i , k, ΔT , $r_{c,min}$ and $r_{c,max}$ are measured, the present model can be used to predict the heat flow from Eq. (20). Meanwhile, K' can be found from $r_{c,max} = K'(\sigma/\rho g)^{1/2}$. Therefore, if the above parameters are measured in experiments, Eq. (20) can be used to predict the heat flow and to compare with experimental data.

5. Concluding remarks

A fractal model for dropwise condensation heat transfer has been derived based on the fractal characteristics of drop size distributions on condensing surfaces and the fractal geometry theory. The proposed model is expressed as a function of fractal dimension of drop size, maximum and minimum drop radii, the temperature difference between condensing surface and saturated steam, and physical properties of fluid. The predicted total heat flux based on the proposed fractal model has been shown to be in good agreement with experimental data. The validity of the present fractal model is thus verified.

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