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液滴微流控高通量可控构建方法的研究进展

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摘 要:微液滴因其显著的界面效应和尺度效应,在化工过程强化、生物医药、功能材料制备等领域具有重要的应用前景。微流控技术因能在微米级通道内对多相流流动进行精确操控,从而为高品质微液滴的可控构建提供了崭新的技术平台;然而,基于微流控技术的单通道结构由于产率低的固有缺陷而无法满足产业化应用需求,亟需发展液滴微流控高通量可控构建方法以实现微液滴构建产率与品质的协同提升。本论文综述了近年来液滴微流控高通量可控构建方法的相关研究进展,重点介绍了基于梯形网络、树形网络与模块化集成等流阻-流量解耦的并行放大策略、基于阶梯乳化和界面浸润诱导失稳等流量-分散解耦的并行放大策略、基于液滴多级对称分裂的倍增量产策略,以及基于离心式驱动、浮力驱动和 3D 打印的三维堆叠式放大策略。此外,介绍了基于并联量产和分裂倍增的复合液滴微流控高通量构建方法,以期为高品质微液滴的微流控高通量可控构建提供科学指导。

关键词:微液滴;微流控;集成放大;高通量构建;多相流

中图分类号:TQ01;TB34

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微液滴因其比表面积大、热质传递效率高、具有天然隔离效应,以及微环境可精准调控等优势,在化工过程强化、生物医药、功能材料制备以及单细胞分析等领域展现出广阔的应用前景^[1-3]。与机械搅拌、超声乳化、膜乳化等传统制备方法相比,微流控技术因能在微米级通道内对多相流流动行为进行精确操控,从而为高品质微液滴的可控构建提供了一种崭新的技术平台。然而,基于微流控技术的液滴制备单元产率较低,通常小于 10 mL/h,无法满足产业化应用需求,已成为微液滴广泛应用的关键瓶颈。因此,发展基于微流控技术的液滴高通量可控构建方法迫在眉睫。目前,基于微流控技术的液滴高通量制备方法主要遵循“数量放大”准则,即通过增大液滴制备单元的数量来实现液滴产率的提升^[4-5]。然而,随着液滴制备单元数量的增加易出现单元之间的流量分配不均,从而导致液滴单分散性变差。此外,对于复合液滴等复杂结构体系,其形成过程涉及多界面耦合,在高通量构建时更易出现稳定性和均一性下降的问题^[6]。因此,液滴

的微流控高通量构建仍面临品质与产率难以协同提升的瓶颈。本文主要介绍了近年来液滴微流控高通量可控构建方法的研究进展,着重介绍了基于树形网络、梯形网络和模块化集成的并联量产,基于阶梯乳化和界面浸润诱导失稳等机制的流量解耦放大方法,基于液滴对称分裂实现倍增量产的构建策略,以及三维堆叠式放大策略。此外,还介绍了基于并联量产和对称分裂的复合液滴微流控高通量可控构建方法。

1 液滴的微流控高通量可控构建方法

1.1 基于并行放大的液滴微流控高通量可控构建方法

并行放大是实现液滴微流控高通量构建最直接且广泛采用的策略,即通过增加液滴制备单元数量来实现液滴产率的线性提升^[4-5]。目前,已发展出并联梯形、并联树形以及模块化集成等多种并行放大结构^[6],然而,随着并联微通道的增多,相距较远的单元之间流阻差异增大,流量分配不均^[7-9],导致液滴均一性下

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降^[10-11]。为此,研究者主要提出了两种解决思路:一是基于流阻-流量解耦的液滴高通量构建;二是基于流量-分散解耦的液滴高通量构建。

1.1.1 基于流阻-流量解耦的液滴高通量可控构建

流阻-流量解耦是指通过对微通道结构设计使得支路通道尽可能满足相同的流动阻力分布,从而实现流量的均匀分配。梯形网络因结构紧凑、几何形状简单、易于集成等优点而成为主要的并行放大网络之一^[12]。图1(a)展示了典型的梯形网络结构,即由两条平行的干路通道(一个分配通道和一个接收通道)以及连接两者的大量分支微通道构成,每个分支微通道通常为一个液滴制备单元。工作时,分散相和连续相分别由两条干路通道引入,在各分支通道的液滴制备单元处生成微液滴并收集。然而,随着并联支路微通道的增多,相距较远的单元之间流阻差异增大,导致流量分配不均,因而造成液滴

均一性下降。为此,研究者假设相邻通道之间的流量差小于0.01即认为每个支路基本满足流量的均匀分配,而第1个和第N个通道的最大流量差为 $2N/K$ (K 为支路通道流阻 R_B 与分配通道流阻 R_D 之比),从而提出了梯形网络中的流量均匀分配定量设计准则($2N/K \leq 0.01$)^[13]。据此,Yadavali等^[14]构建了硅和玻璃的超大规模并联微流控液滴制备装置,在单个装置中集成了10 260个流动聚焦液滴制备单元,液滴生成频率超过 2.7×10^8 。然而,这种推导规则忽略了前后分布微通道之间的流动变化,打破了流动分布的均匀性^[15]。基于此,Deng等^[15]提出了一种倒推流动分析(backstepping microflow analysis, BMA)的梯形网络设计方法。首先,假设各分支通道内流量 Q_a 完全均匀,利用倒推法建立从出口到入口的流阻递推关系;然后,通过最小化并联通道中任意两个支路的阻力差,推导出逆流操作与顺流操作需满足的定量

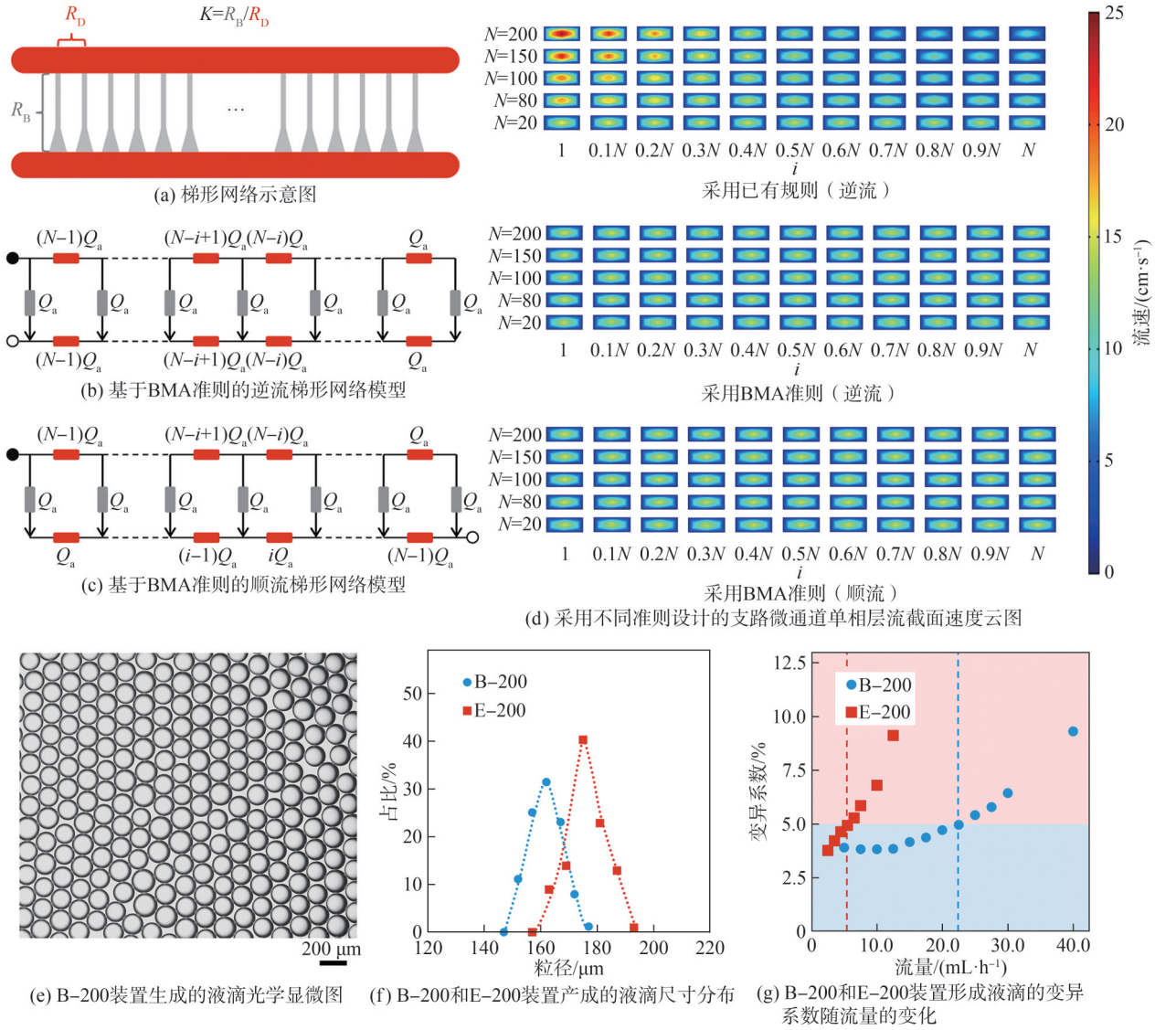


图1 基于BMA的并联梯形网络用于单分散微液滴高通量制备^[15]

Fig. 1 BMA-based microfluidic ladder networks for high-throughput generation of microdroplets^[15]

条件。如图 1(b)、(c)所示,逆流时, $N^2/K \leq 0.01$;而顺流时, $0.25N^2/K \leq 0.01$ 。图 1(b)~(d)中, i 取 $1 \sim N$ 。与前述设计准则对比发现,BMA 设计的网络在分支通道内流速更均匀,如图 1(d)所示。同时,采用 BMA 准则制备的含 200 个液滴制备单元的共流梯形网络(B-200)在分散相和连续相流速各为 2.5 mL/h 时,可生成平均直径约 159.53 μm 、变异系数(coefficient of variation, CV)为 3.81% 的单分散液滴,如图 1(e)所示,相比于已有规则设计的 E-200 装置,生成液滴单分散性更好,如图 1(f)所示。更重要的是,B-200 装置可在更宽的流速范围内使 CV 维持在小于 5% 的水平,显著优于已有规则设计的 E-200 装置,如图 1(g)所示。

梯形网络因每个液滴制备单元流体路径不同,存在流体分配不均的固有缺点,而树形网络由于每个单元路径的高度对称性成为液滴制备单元并行放大的另一类主要流体分配网络。如图 2(a)、(b)所示,该结构通常由一根主干通道起始(第 0 级),经 n 次对称二分叉(“Y”形或“T”形节点)逐级延伸,形成层级递进的树状结构。每经一级分支,通道数量翻倍,最终在末端产生 2^n 个并行子通道。树形网络的核心设计原则在于其结构上的严格对称性。由于微通道内的流动通常为层流,因此几何对称进一步保证了流体流动对称性,

从而自发实现均匀的流量分配^[4,16]。Li 等^[9]基于 128 个流动聚焦单元的树形网络,实现了 50 g/h 聚 N-异丙基丙烯酰胺颗粒的制备, CV 小于 5%。Nisisako 等^[17]通过 144 个流动聚焦单元的树形网络实现了 180 mL/h 的微液滴构建, CV 小于 2%。理论上,树形网络因高度对称性克服了并行微通道中的流量分配不均,然而,实际操作中,随着分叉次数的增多,微通道尺寸逐级变小,容易造成通道堵塞,而个别通道的堵塞将会影响整个系统流量分配的均匀性。对此,Conchouso 等^[18]设计了一种三维可堆叠流动聚焦液滴制备单元阵列。该装置采用分形树状对称分配网络,将每层 128 个液滴生成单元分为 4 组,每组有独立的输入和输出通道,仅在最高层级连接。这种结构能在一定程度上缓解通道堵塞问题,即使某个层发生堵塞,只需关闭该层的输入或输出并适当调整压力,其余层仍能正常工作,保持原有液滴尺寸和分布均匀性,如图 2(c)~(e)所示。然而,树形网络虽然能提高流体分配的均匀性,但空间利用率偏低,且随着分支级数增加,末端通道扇形范围急剧扩张,大量芯片面积被分配流道占据,限制了功能单元的集成密度;其次,在树形网络中,任一支路发生堵塞都会破坏网络的对称流阻平衡,导致流量重新分配并沿层级传导^[4,19-20]。

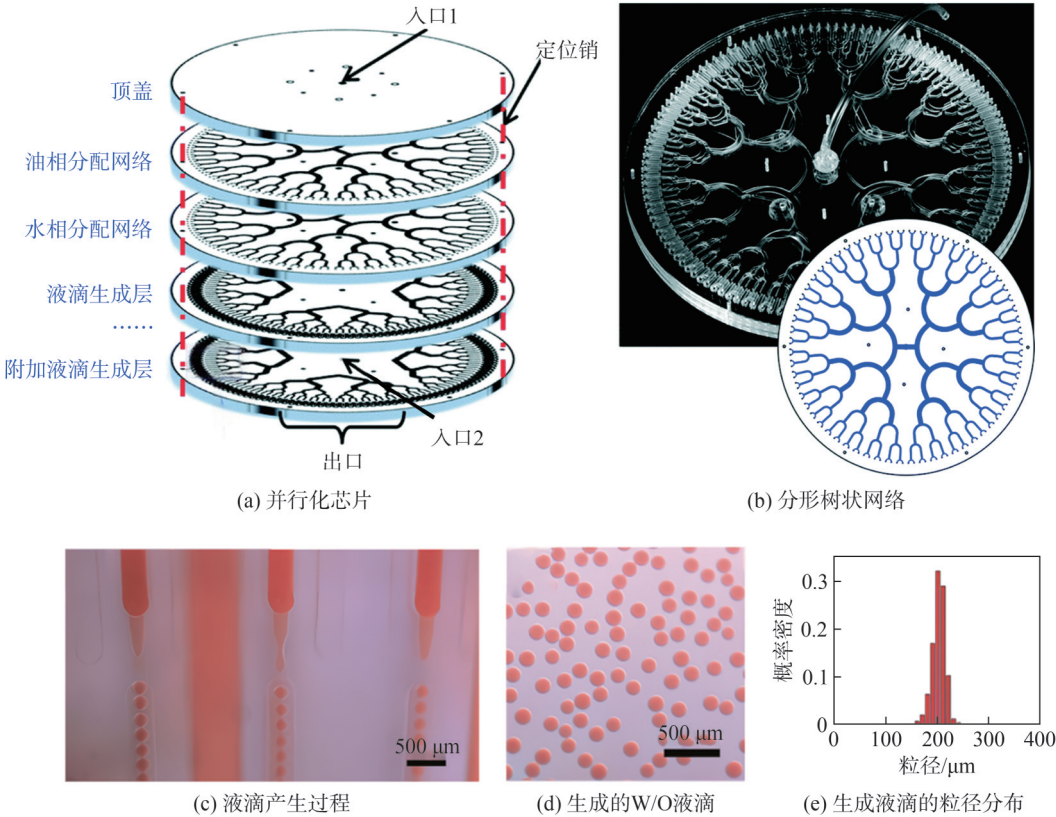


图 2 基于并联树形网络的液滴高通量构建^[18]

Fig. 2 High-throughput generation of microdroplets based on parallel tree-like networks^[18]

尽管上述提到的梯形网络和树形网络在一定条件下能改善流量分配的均匀性,然而,传统的一体式微流控芯片在面对通道堵塞、规模扩展受限,以及设计灵活性等问题时仍存在局限^[21-23]。为此,研究者提出了模块化集成,即将复杂的系统拆分为若干个可独立组装和替换的模块,其核心优势主要体现在3个方面:一是可更换,即当某个液滴生成模块发生堵塞或泄漏时,无须废弃整个系统,仅快速替换故障模块即可恢复生产,如Li等^[9]提出的多模块微流控反应器,每个模块包含16个平行的微通道,分别承担乳化和聚合功能,故障后及时更换,不会影响后续设备使用;二是可扩展,即通过增加模块数量(如堆叠更多层或串联更多级)实现通量提升,无须重新设计芯片整体结构,如Han等^[24]设计了由8通道单阵列和10层垂直堆叠组成的并行放大模块(80个液滴制备单元),并通过集成5个相同模块,将总通道数扩展至400,显著提升了

微通道数量;三是设计灵活,即模块化集成将复杂的流动分配网络拆分为可独立优化和组装的标准单元,摆脱了一体式芯片中所有通道尺寸必须满足严格耦合约束的困境,能够针对不同流体性质和工艺要求灵活调整局部设计。

据此,Deng等^[22]进一步提出了灵活分形集成策略(FFI),如图3(a)~(c)所示,将“H”形分形网络用于流体均匀分配,并与并联液滴制备模块相结合,构建了包含256个液滴制备单元的模块化系统。图3(a)中, r 为流量分配模块中的流阻,图3(c)中, $S-0\sim S-m$ 表示嵌套级数。该分形网络能够在较宽的结构尺寸范围内实现流量的均匀分配,使系统在大规模扩展条件下仍保持良好的运行稳定性,且制备液滴的CV小于2%,实现数百毫升每小时的单分散微液滴连续生产,如图3(d)~(f)所示,进一步提升了模块化微流控系统的可扩展性与工程应用潜力。

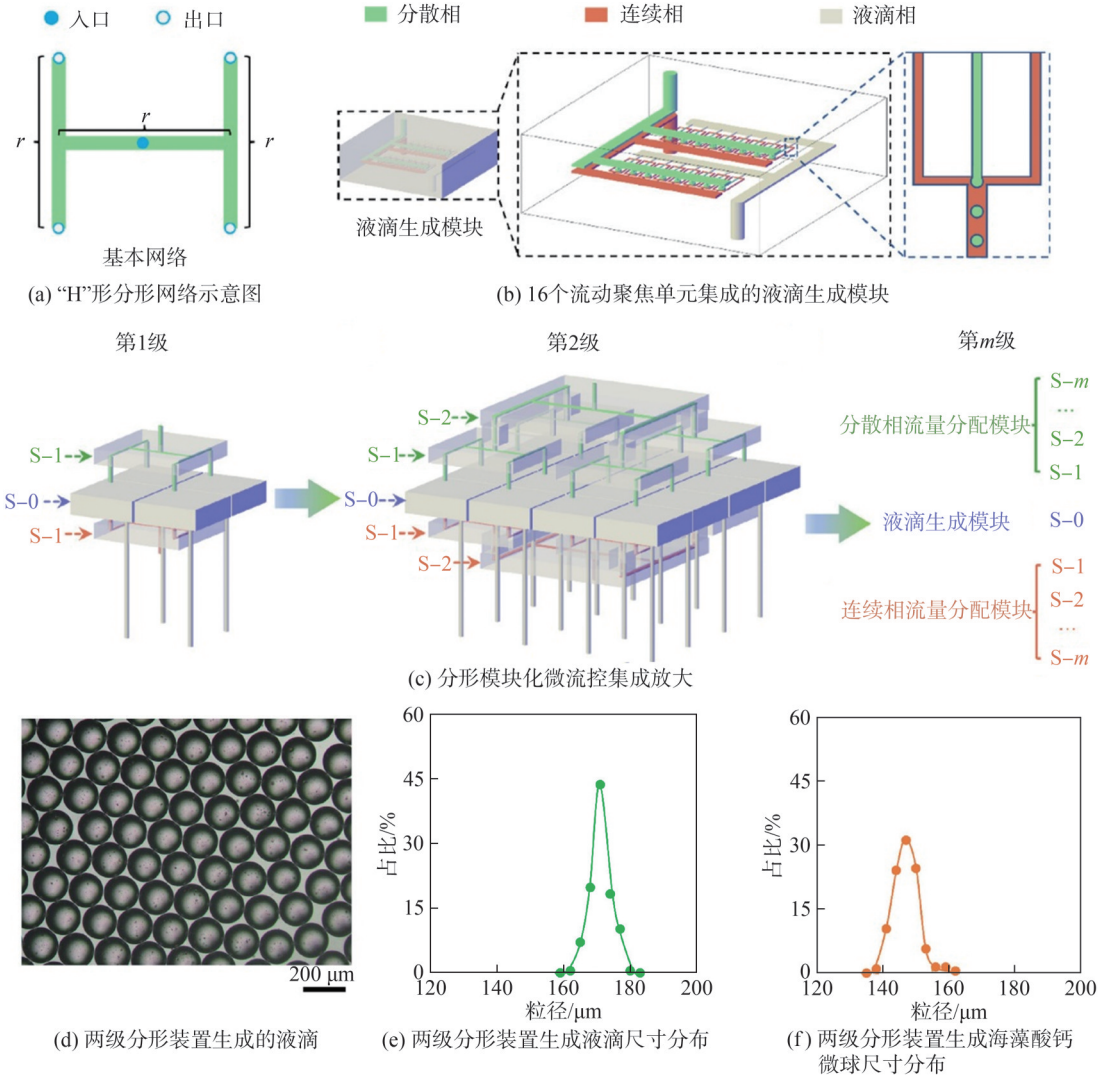


图3 基于模块化分形微通道网络的液滴微流控集成放大^[22]
Fig. 3 Fractal modular microfluidic system for high-throughput of microdroplets^[22]

1.1.2 基于流量-分散解耦的液滴高通量可控构建

如前所述,梯形网络、树形网络和模块化集成等传统并行放大方法高度依赖多通道间的流量分配,流量分配的均匀性直接影响了液滴单分散性。从另一个角度,研究者提出了液滴生成过程与流量参数解耦的新策略,典型的有基于阶梯乳化单元的液滴高通量构建方法。与传统依赖连续相剪切力实现液滴断裂的“T”形或流动聚焦等主动剪切方式不同,基于阶梯乳化单元的液滴生成主要依赖微通道出口处几何结构突变导致的界面曲率变化所产生的拉普拉斯压差,使得液滴尺寸主要由微通道的几何参数决定,而非受两相流量控

制^[25-27],如图4(a)、(b)所示。Ofner等^[28]设计了含364个线性并行液滴制备单元的玻璃芯片,液滴尺寸几乎不随分散相和连续相流速变化,证明了阶梯乳化中液滴尺寸与流动参数的解耦,最终以高达25 mL/h的分散相流量稳定生产单分散液滴,CV值低至2.8%,且能连续运行10 h保持稳定。如图4(c)、(d)所示,Dangla等^[29]成功实现了256个液滴制备单元并行的规模化集成,在 $Q=20\text{ }\mu\text{L/min}$ 的分散相流速下,该装置产生体积 $226\pm16\text{ pL}$ 、频率1.5 kHz的单分散液滴。然而,基于阶梯乳化的微流控构建方法对分散相与通道的浸润性有较高的要求,即接触角须大于 120° ,否则难以产生单分散的液滴。

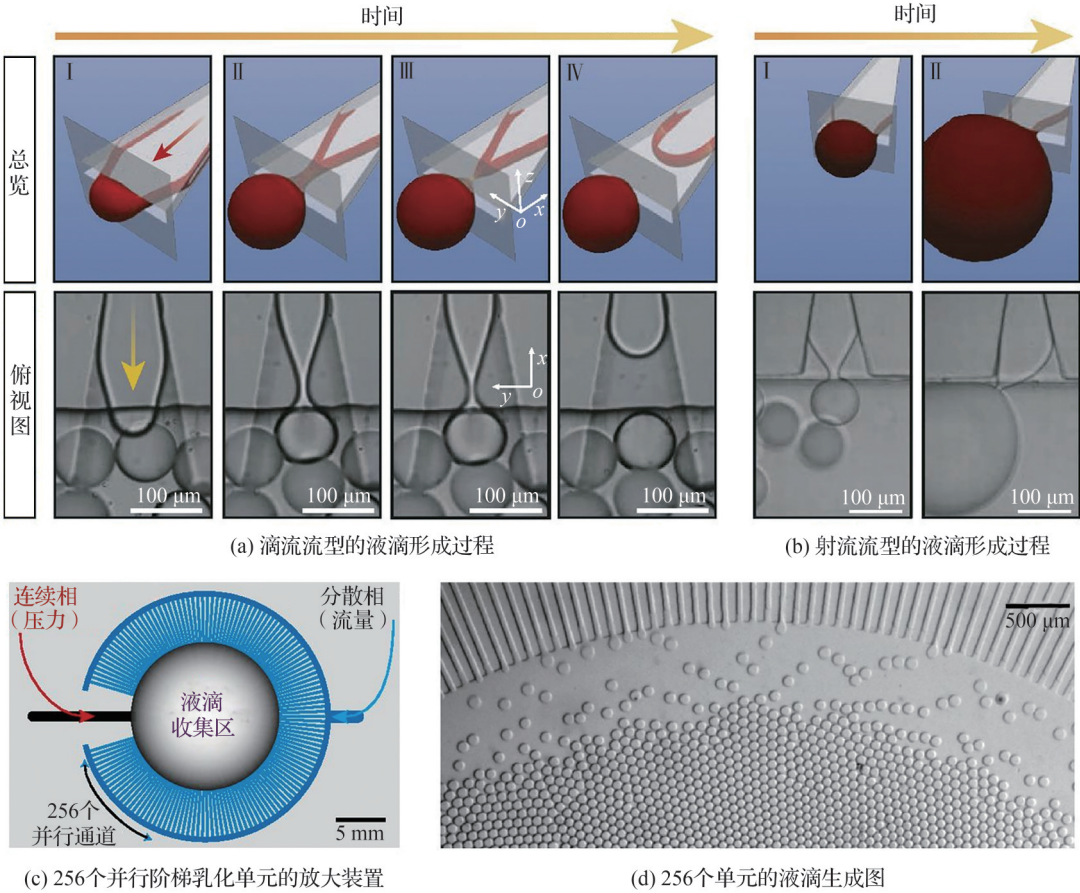


图 4 基于阶梯乳化的液滴形成及高通量构建^[28-29]

Fig. 4 High-throughput generation of microdroplets based on step emulsification^[28-29]

在最近的研究中,Su等^[30]提出了基于浸润诱导界面不稳定的流量解耦液滴生成新策略。该方法主要由界面张力和润湿作用主导,如图5(a)所示,分散相从锥口末端挤出,形成一个悬挂液滴,当悬挂液滴下降至与下方不混溶的连续相接触时,连续相会自发沿液滴表面上铺展,产生向下的界面力,打破原有的受力平衡,使液滴根部迅速颈缩,发生断裂,最终在连续相中形成尺寸均一的微液滴。这一过程中,三相接触线处产生了由界面能主导的向下驱动力,使液滴的断裂主要由锥口到气-液界面的垂直距离决定,与分散相流速、锥口直径以及

流体物性显著解耦。同时,该方法具备良好的可扩展性,如图5(b)、(c)所示,采用16个并行锥口的放大装置可在640 mL/h的分散相流量下以2 451的频率生成单分散液滴,CV值仅为2.9%,且可以乳化黏度高达56 600 mPa·s的分散相液滴。

1.2 基于对称分裂的液滴微流控高通量可控构建方法

与液滴制备单元的并行放大不同,对生成液滴进行二次操控,通过多级对称分裂实现液滴的倍增量产是另一种液滴高通量构建策略。如图6(a)、(b)所示,对称分裂集成放大系统多采用树状分叉网络,在对称

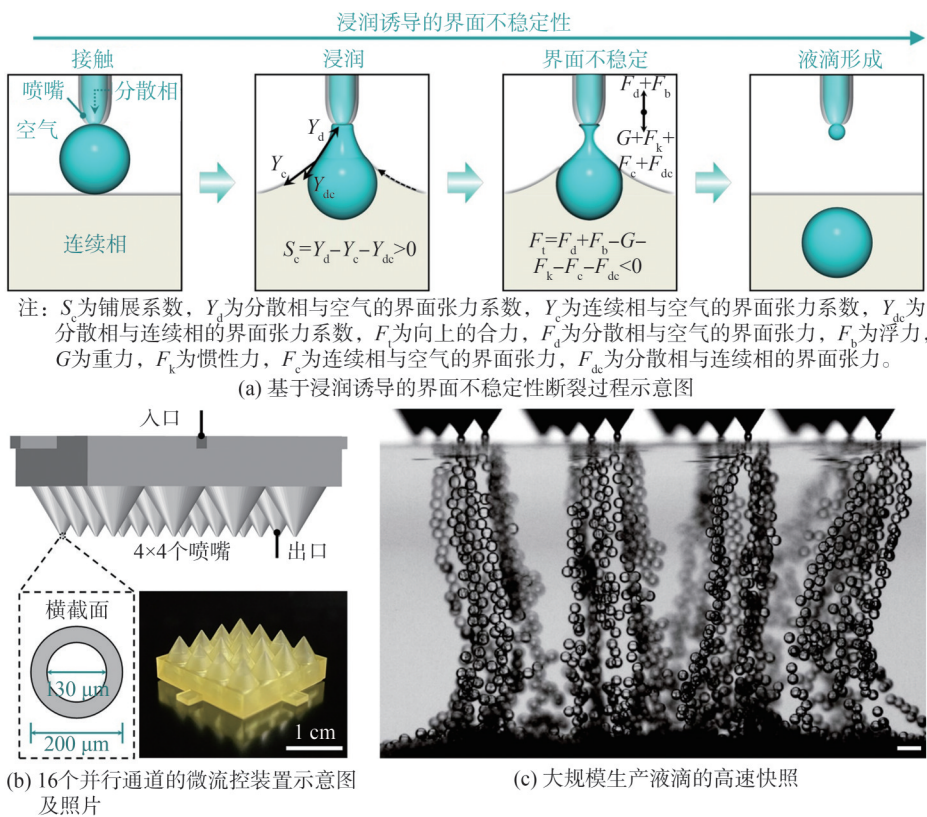
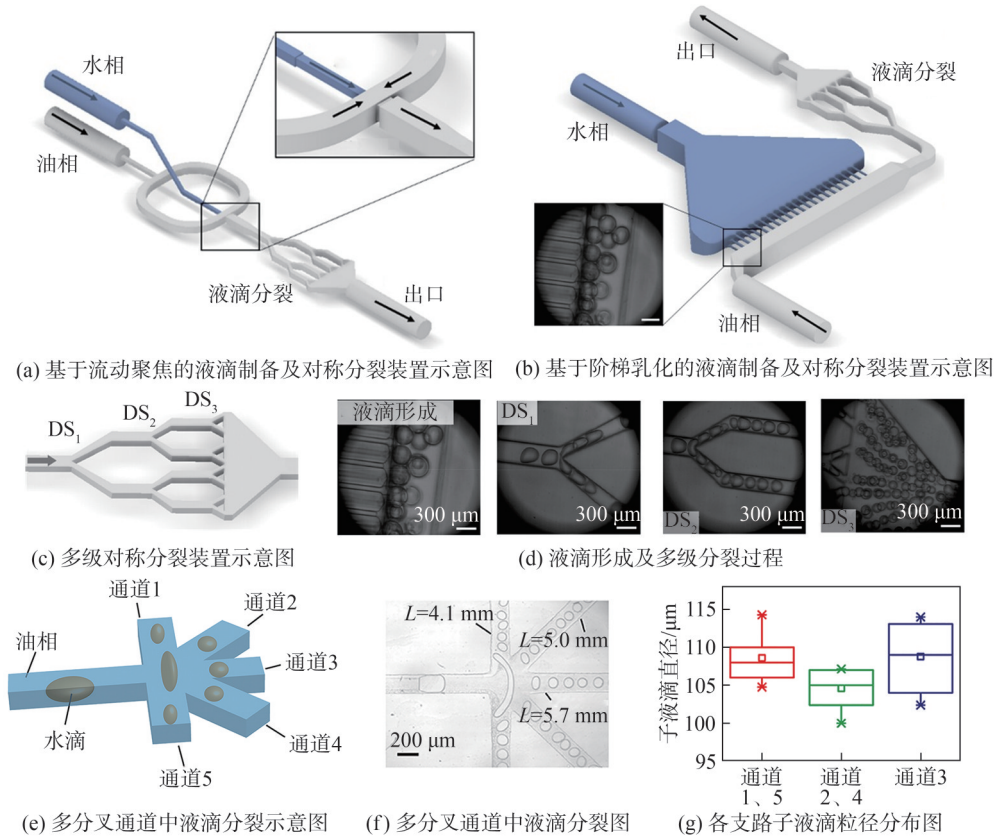


图 5 基于浸润诱导界面不稳定的液滴形成及高通量构建^[30]

Fig. 5 High-throughput generation of microdroplets based on wetting-induced interfacial instability^[30]



注: DS₁、DS₂、DS₃ 分别为液滴第 1、2、3 次分裂, L 为通道长度。

图 6 基于对称分裂的液滴高通量构建^[33-34]

Fig. 6 High-throughput generation of microdroplets based on symmetric splitting^[33-34]

的“Y”形分叉通道中,两侧分支的流体阻力相等,因此液滴在两个分支中的延伸速度和体积流量一致,从而实现等体积分裂,大液滴通过多级通道依次等分为更小的液滴,随着分裂次数 n 的增加,液滴数量呈 2^n 倍增^[31-32]。Vigogne 等^[33]采用三级液滴分裂装置,将初始液滴数量增至 8 倍,如图 6(c)、(d)所示,液滴直径从约 300 μm 逐步缩小至约 150 μm ,并成功制备出 CV 值为 3%~5%的聚丙烯酰胺微凝胶;Li 等^[34]则在“Y”形二分裂的基础上设计了多分叉(1分5)微通道,当液滴足够大时,可以完全占据通道,此时 5 个分支中的子液滴体积趋于相等,如图 6(e)~(g)所示。基于对称分裂的集成放大技术具有单芯片高集成度和低复杂度的优势,属于简单的二维结构,容易加工制造,显著提升生产效率,为液滴微流控高通量构建提供了一条核心技术路径^[32,35]。

1.3 基于三维结构的液滴微流控高通量可控构建方法

除了基于平面式的并行放大和对称分裂倍增等策略,离心式微流控和三维堆叠微流控结构由于空间集成密度大的优势也为微液滴的高通量构建提供了重要的技术路径。

离心式微流控主要利用旋转产生的离心力驱动分散相流体流出喷嘴,在无需外接注射泵的条件下实现液滴生成,具有结构紧凑、死体积小和易于集成等优势。

Schuler 等^[36]提出离心式阶梯乳化方法制备了液滴直径在 120~170 μm 的单分散液滴,CV 值为 2%~4%,单个喷嘴的液滴产生频率超过 500,且液滴尺寸在 0.01~1.00 $\mu\text{L/s}$ 的分散相流量范围内基本不受流量波动的影响。随后,进一步构建了含 72 个喷嘴的离心式高通量设备,可制备高内相比乳液,在 20 Hz 转速下液滴直径约 156 μm ,产生频率达到 3 700,CV 小于 4%^[37]。该研究团队在离心力场中引入了浮力驱动,进一步提高了液滴产生频率,当制备 100 μm 液滴时,在 100 Hz 的旋转频率下,单个喷嘴的产生频率超过了 2 800^[38]。

三维堆叠结构主要通过空间维度拓展液滴制备单元的数量,以提高单位芯片内的液滴制备通量。Jeong 等^[6]报道了三维单体弹性体器件 3D MED,在单个弹性体结构中集成 1 000 个并联的流动聚焦液滴制备单元,可在 1.5 L/h 的通量下制备直径约 45 μm 的微液滴,CV 值为 6.6%,生成频率超过 8.7×10^6 。此外,3D 打印技术的快速发展,也为三维堆叠式的液滴微流控高通量构建装置的加工带来了便利。Fimmer 等^[39]通过 3D 打印技术构建了垂直堆叠式放大装置,堆叠了 28 个流动聚焦单元,制备通量达到 3 L/h,500 μm 粒径的微液滴产生频率达 1.3×10^4 。上述不同液滴微流控高通量构建方法的性能对比见表 1。

表 1 不同放大方法下的液滴微流控高通量构建

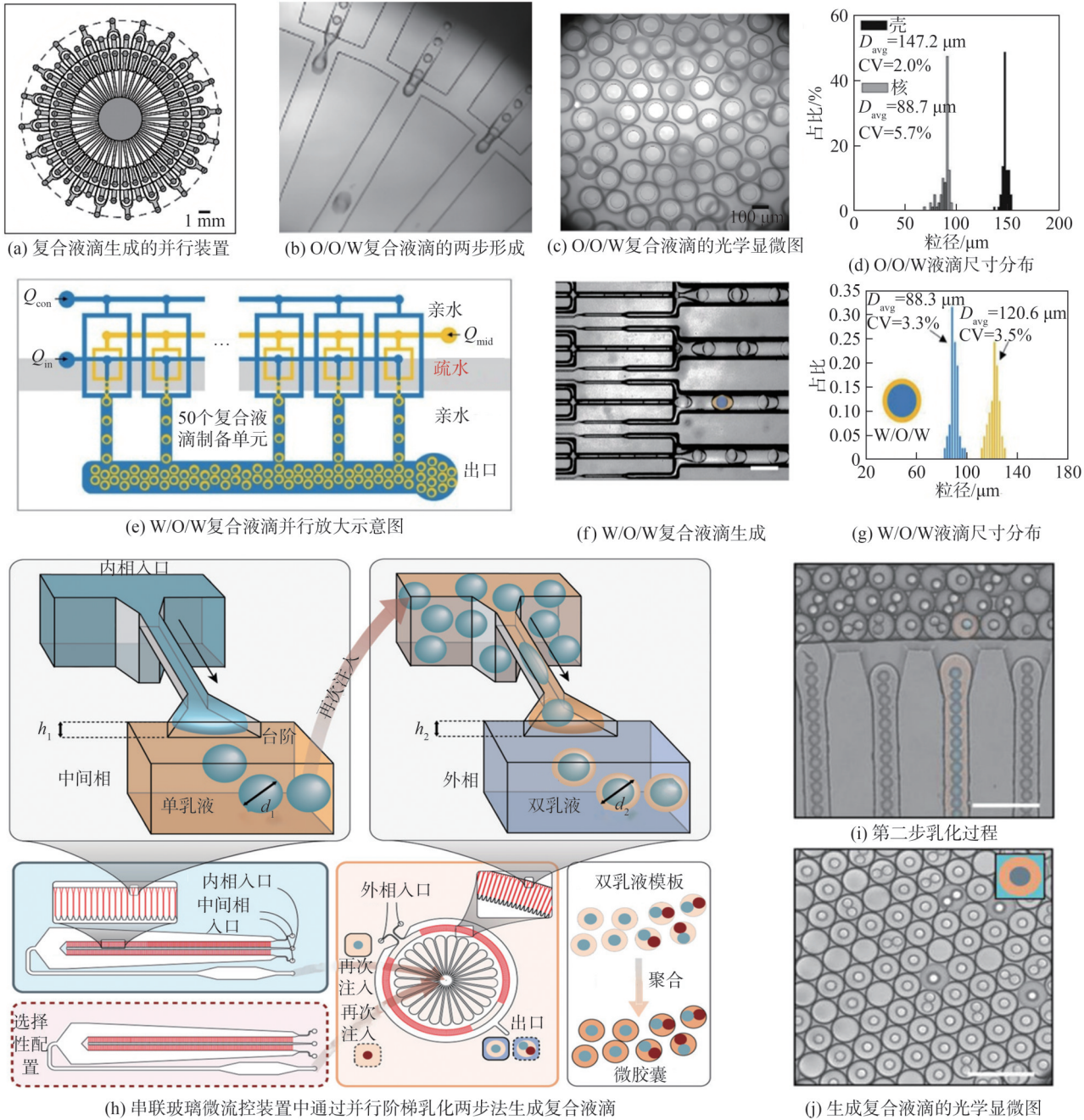
Tab. 1 High-throughput generation of microdroplets with microfluidics

来源	高通量构建方法	分散相通量/ ($\text{mL}\cdot\text{h}^{-1}$)	并行通道数量	液滴产生频率	CV 值/%	液滴粒径/ μm	分散相黏度/ ($\text{mPa}\cdot\text{s}$)	加工材质	结构复杂度	抗堵塞	成本
文献[19]	梯形网络		180		4.7	19.8~22.8	1~40	PMMA	复杂	一般	中
文献[20]	梯形网络		32	5×10^4	4.2	78.84~80.35	1	3D 打印	一般	好	低
文献[40]	梯形网络	8	512	6.7×10^4	9	86.1		PDMS	一般	一般	中
文献[14]	梯形网络	2 090	10 260	2.7×10^8	3	23~42	0.43~30	硅/玻璃	复杂	好	高
文献[7]	树形网络	5	10		7	64~86	1	PDMS	简单	一般	低
文献[17]	树形网络	180	144	856	2.2	90.7	6.35	玻璃	复杂	一般	高
文献[18]	树形网络	1 000	512		6	100~200	1	PMMA	复杂	差	中
文献[9]	模块化集成	51.2	128		3.7	82~144	1~1.25	PDMS	一般	好	低
文献[22]	模块化集成	66.5	256		1.9	124~188		PDMS	一般	好	低
文献[24]	模块化集成	6 000	400		7	872.8~951.8	1~500	PMMA	一般	好	中
文献[12]	阶梯乳化	63	50		2.6	176.2	1.003	PDMS	简单	好	低
文献[15]	阶梯乳化	30	200		3.8	159.53		PDMS	一般	一般	低
文献[27]	阶梯乳化	25	364		4.6	69.7~101.0		玻璃	复杂	一般	高
文献[28]	阶梯乳化	1.2	256	1.47×10^3	7	73~82	0.02~4.1	PDMS	简单	一般	低
文献[30]	界面浸润	640	16	2.45×10^3	2.9	517.5	1~56 600	3D 打印	简单	好	中
文献[33]	对称分裂	10	480		8	148	1.002	3D 打印	一般	一般	中
文献[34]	对称分裂	0.6	8		5	105~185	1	PDMS	简单	好	低
文献[36]	离心式	3.6	23	1.15×10^4	4	120~170	1	PMMA	一般	好	中
文献[38]	离心式		1	2.8×10^3	5	100	1	PMMA	一般	好	中
文献[37]	离心式	48.6	72	3.7×10^3	4	156		PMMA	一般	好	高
文献[39]	3D 打印堆叠	3 000	28		4.8	350~550	1	3D 打印	简单	好	中
文献[41]	3D 打印堆叠	180	15		10	150~1 000	1	3D 打印	简单	好	中
文献[6]	3D 打印堆叠	1 500	1 000		6	36.2~51.2	1	PDMS	简单	一般	高

2 复合液滴的微流控高通量可控构建方法

相较于单液滴,复合液滴因独特的核-壳结构而在药物递送^[42-45]、细胞封装以及先进功能材料制备等领域受到广泛关注。然而,多界面的引入使得复合液滴的形成过程涉及更复杂的流体动力学与界面稳定性问题。一方面,复合液滴的形成通常需要连续完成两次乳化,因此,不同体系需要针对不同区域进行相应的润湿性调控;另一方面,由于分散相增多,需要同时兼顾内相和中

间相的流量分配,因此,其高通量可控构建面临通道壁面浸润性调控和多相流量均匀分配的双重挑战^[46-47]。在未对通道进行选择表面改性时,通道壁面浸润性是一致的,此时,复合液滴的制备局限于内相和中间相与通道浸润性一致的情形,如 O/O/W 或 W/W/O 结构。Nisisako 等^[17]设计了一种带有同轴环形接口的微流控平台,制备了 O/O/W 复合液滴,内核 CV 为 5.7%,外壳 CV 为 2.0%,如图 7(a)~(d)所示。然而,对于 W/O/W 或 O/W/O 复合液滴体系,内层乳化与外层乳化过程对应不同的连续



注: Q_{con} 为连续相流体, Q_{in} 为内相流体, Q_{mid} 为中间相流体, D_{avg} 为平均粒径, h_1 为第 1 级阶梯乳化的通道高度, h_2 为第 2 级阶梯乳化的通道高度, d_1 为第 1 级阶梯乳化产生液滴的直径, d_2 为第 2 级阶梯乳化产生复合液滴的外径。

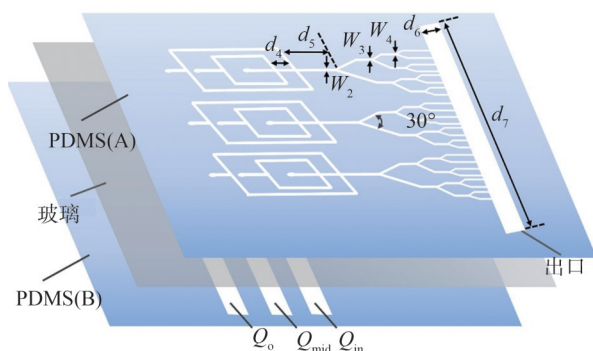
图 7 基于并联量产的复合液滴微流控高通量构建^[17,48,50]
Fig. 7 High-throughput generation of compound microdroplets based on parallel channels^[17,48,50]

相环境,因此要求液滴生成区域具有不同的界面润湿特征,故需对微通道进行图案化的局部改性。Wu等^[46]通过光刻技术在硅/玻璃芯片上实现了微米级精度的空间润湿性图案化,通过倾斜紫外曝光实现了三维通道侧壁的统一改性,并利用高稳定性的全氟辛基三氯硅烷选择性构建疏水区域,从而成功制备了W/O/W和O/W/O两种类型的复合液滴,并进一步集成了50个复合液滴制备单元,实现了30 mL/h的复合液滴高通量构建,内外径CV均小于5%,如图7(e)~(g)所示。

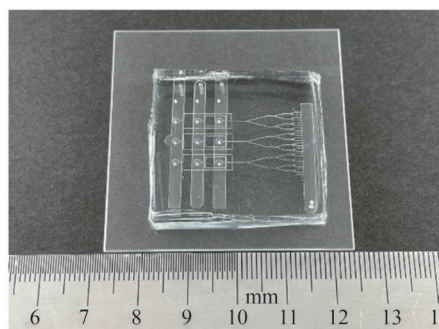
与依赖润湿性图案化的策略不同,两步阶梯乳化通过先成核、后包裹的串联几何结构实现复合液滴的高通量制备,其中第一级阶梯乳化首先产生单分散的内核液滴,第二级装置则将含有内核的中间相再次通过台阶结构,在外相中乳化形成复合液滴^[49],这种设计有效避开了润湿性改性的工艺瓶颈。如图7(h)所示,Ofner等^[50]提出了两步串联阶梯乳化策略用于高通量制备复合液滴。通过调控两级台阶高度比,可分别制备薄壳型($d_1/d_2>1$ 、壳厚3 μm 、CV为4.2%)、厚壳型($0.6<d_1/d_2<1$ 、CV为2.4%)和多核型($d_1/d_2<0.6$ 、CV

为4.6%)复合液滴,并集成了1 000个液滴制备单元,通量高达50 mL/h,可连续稳定运行超过5 h。然而,该两步法存在两级液滴生成频率难以匹配的问题,使得复合液滴的内核数量无法定量控制,导致其单分散性差,如图7(i)~(j)所示。

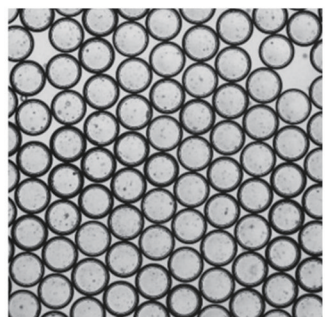
与单液滴对称分裂的集成放大类似,复合液滴也可通过对称分裂实现产率倍增与尺寸调控。Liu等^[51]系统研究了双重乳液在“Y”形微通道中的破裂模式,建立了流速比、液滴尺寸与破裂行为之间的关系,揭示了对称分裂、非对称分裂及不完全破裂等典型机制。在此基础上,Fan等^[52]提出了多通道并联与多级分裂相耦合的复合液滴集成放大新策略,即首先通过复合液滴制备单元的并联实现第一次量产,而后串联多级“Y”形分裂,实现 2^n 倍增。由此设计了多通道并联与三级对称分裂耦合的微流控网络,如图8(a)~(c)所示,所得核层液滴和壳层液滴的CV值分别为3.79%和2.85%,具有优异的单分散性。而后以该双乳液为模板,通过UV固化中间相成功制备了高单分散性的聚乙氧基化三羟甲基丙烷三丙烯酸酯微胶囊,如图8(d)、(e)所示。



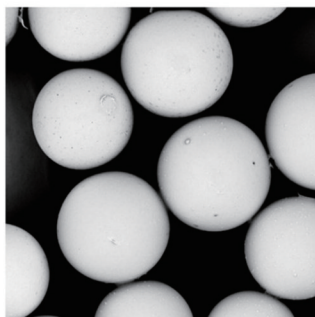
(a) 并行三级分裂微流控芯片结构示意图



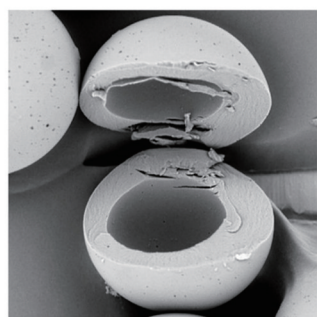
(b) 并行三级分裂微流控芯片实物图



(c) 三级分裂后的液滴光学显微图



(d) 单分散PETPTA微胶囊图



(e) PETPTA微胶囊切面

注:PDMS为聚二甲基硅氧烷, Q_o 为外相流体, d_4 为中间相与外相通道之间的距离, d_5 为外相通道与第1次分裂之间的距离, d_6 为接收通道宽度, d_7 为接收通道长度, W_2 为液滴产生通道的宽度, W_3 为液滴第1次分裂后通道的宽度, W_4 为液滴第2次分裂后通道的宽度。

图8 基于可控对称分裂的复合液滴制备^[52]

Fig. 8 Preparation of compound microdroplets based on controllable symmetric splitting^[52]

3 结论与展望

尽管液滴微流控技术能实现液滴尺寸和品质的精准调控,但单通道结构所固有的产率瓶颈限制了其

工业化应用,因此,亟需发展基于微流控技术的液滴高通量构建方法。基于梯形网络、树形网络和模块化集成的并行放大策略通过增加液滴制备单元数量实现了产率提升,并通过优化多相流分配网络改善了液

滴的均一性,其中,梯形网络集成密度高、树形网络结构对称性强、模块化集成则兼具可更换和可扩展的工程化潜力。然而,该类方法本质上仍属于流量耦合型液滴生成模式,其性能高度依赖多通道间流量的均匀分配,当并联规模进一步扩大时,易出现流量分配不均,从而导致液滴单分散性急剧下降的问题。为此,进一步发展出基于阶梯乳化、界面浸润诱导失稳等的流量解耦放大策略。该类方法利用界面张力主导的液滴形成机制,使液滴尺寸主要由微通道几何结构或界面润湿行为决定,而对流量变化不敏感,从而显著降低了大规模并联条件下对流量均匀分配的要求,但其流体体系种类和黏度范围等仍有一定的局限性。与增加液滴制备单元数量的思路不同,对称分裂策略通过几何约束诱导液滴连续分裂,实现对液滴数量的倍增放大,具有结构紧凑、放大效率高等优势,但多级连续分裂中的液滴稳定性、尺寸变化规律及界面稳定机制仍有待深入研究。除了基于平面式的并行放大和对称分裂倍增等策略,三维结构微流控装置由于空间集成密度大的优势也为微液滴的高通量构建提供了重要的技术平台。该类方法通过离心力、浮力驱动、垂直堆叠等结构,进一步突破了单位芯片的液滴制备通量。此外,并联量产和分裂倍增等方法也被应用于复合液滴的微流控高通量构建。然而,相较于单液滴体系,复合液滴涉及多界面协同演化和润湿行为调控,其高通量构建仍面临多相流体分配均匀性、液滴包封稳定性等挑战。

目前,液滴微流控高通量构建策略已实现液滴的高通量制备,但仍存在产率与品质协同提升的挑战,主要体现在:并行通道之间的流阻差异、加工误差和压力波动容易导致流量分配不均,从而降低液滴尺寸均一性;液滴高通量构建尚无法实现连续稳定生成,且生成后的固化、洗涤、分离和收集等后处理过程难以连续化集成。

为此,可从以下方面进行研究:1)发展基于物理信息增强的神经网络进行复杂微通道网络流阻智能设计,即将微通道中的质量守恒、压力平衡、流阻关系等嵌入神经网络和优化算法中,建立兼具物理约束与数据学习能力的流阻智能设计模型。通过对通道数量、长、宽、高和流阻补偿等结构进行反向优化,从而实现流量的均匀分配,提高液滴的单分散性^[53-54];2)建立流量解耦的阶梯乳化单元与并联量产、分裂倍增量产相结合的分步多级式放大系统,以同时缓解并联通道数量与分裂级数的压力,由此突破单一量产模式的瓶颈,实现微液滴产率与品质的协同提升;3)搭建液滴高通量构建过程的智能调控平台,即结合高速显微成像、机器视觉识别和实时控制算法,建立液滴生

成过程的在线感知系统,对液滴直径、单分散性、生成频率和异常液滴进行实时监测^[55-56],并将识别结果反馈至流量调节模块,实现操作条件的自适应调节,从而实现微液滴的高通量连续精准制备。

参考文献:

- [1] Nan Lang, Zhang Huidan, Weitz D A, et al. Development and future of droplet microfluidics[J]. *Lab on a Chip*, 2024, 24(5): 1135–1153.
- [2] Saeed M M, Carthy E, Dunne N, et al. Advances in nanoparticle synthesis assisted by microfluidics[J]. *Lab on a Chip*, 2025, 25(13): 3060–3093.
- [3] Chen Kangfu, Yang Hongfen, Cai Ren. Microfluidics for nanomedicine delivery[J]. *ACS Biomaterials Science & Engineering*, 2025, 11(2): 774–783.
- [4] Jeong H H, Issadore D, Lee D. Recent developments in scale-up of microfluidic emulsion generation *via* parallelization[J]. *Korean Journal of Chemical Engineering*, 2016, 33(6): 1757–1766.
- [5] Shen Qiying, Zhang Chong, Tahir M F, et al. Numbering-up strategies of micro-chemical process: Uniformity of distribution of multiphase flow in parallel microchannels[J]. *Chemical Engineering and Processing—Process Intensification*, 2018, 132: 148–159.
- [6] Jeong H H, Yelleswarapu V R, Yadavali S, et al. Kilo-scale droplet generation in three-dimensional monolithic elastomer device (3D MED)[J]. *Lab on a Chip*, 2015, 15(23): 4387–4392.
- [7] Amstad E, Chen Xiaoming, Eggersdorfer M, et al. Parallelization of microfluidic flow-focusing devices[J]. *Physical Review E*, 2017, 95(4): 043105.
- [8] Li Wei, Young E W K, Seo M, et al. Simultaneous generation of droplets with different dimensions in parallel integrated microfluidic droplet generators[J]. *Soft Matter*, 2008, 4(2): 258–262.
- [9] Li Wei, Greener J, Voicu D, et al. Multiple modular microfluidic (M3) reactors for the synthesis of polymer particles[J]. *Lab on a Chip*, 2009, 9(18): 2715.
- [10] Ward T, Faivre M, Abkarian M, et al. Microfluidic flow focusing: Drop size and scaling in pressure versus flow-rate-driven pumping[J]. *Electrophoresis*, 2005, 26(19): 3716–3724.
- [11] Chen Xiaoming, Glawdel T, Cui Naiwen, et al. Model of droplet generation in flow focusing generators operating in the squeezing regime[J]. *Microfluidics and Nanofluidics*, 2015, 18(5): 1341–1353.
- [12] Zhang Meng, Li Jiang, Liang Shuaishuai, et al. Designable microfluidic ladder network with gradually varying resistance for mass production of monodisperse droplets[J]. *Mi-*

- crofluidics and Nanofluidics,2025,29(9):60.
- [13] Romanowsky M B, Abate A R, Rotem A, et al. High throughput production of single core double emulsions in a parallelized microfluidic device[J]. *Lab on a Chip*, 2012, 12(4):802.
- [14] Yadavali S, Jeong H H, Lee D, et al. Silicon and glass very large scale microfluidic droplet integration for terascale generation of polymer microparticles[J]. *Nature Communications*, 2018, 9:1222.
- [15] Deng Chuanfu, Su Yaoyao, Yang Shihao, et al. Designable microfluidic ladder networks from backstepping micro-flow analysis for mass production of monodisperse microdroplets[J]. *Lab on a Chip*, 2022, 22(24):4962–4973.
- [16] Wu Jingyu, Yadavali S, Lee D, et al. Scaling up the throughput of microfluidic droplet-based materials synthesis: A review of recent progress and outlook[J]. *Applied Physics Reviews*, 2021, 8(3):031304.
- [17] Nisisako T, Ando T, Hatsuzawa T. High-volume production of single and compound emulsions in a microfluidic parallelization arrangement coupled with coaxial annular world-to-chip interfaces[J]. *Lab on a Chip*, 2012, 12(18):3426.
- [18] Conchouso D, Castro D, Khan S A, et al. Three-dimensional parallelization of microfluidic droplet generators for a litre per hour volume production of single emulsions[J]. *Lab on a Chip*, 2014, 14(16):3011–3020.
- [19] Tetradis-Meris G, Rossetti D, Pulido de Torres C, et al. Novel parallel integration of microfluidic device network for emulsion formation[J]. *Industrial & Engineering Chemistry Research*, 2009, 48(19):8881–8889.
- [20] Aladese A D, Jeong H H. Numerical and experimental investigations of uniform fluid distribution for droplet formation in parallelized microfluidics[J]. *Frontiers in Sensors*, 2022, 3:1014864.
- [21] Wu Jialin, Fang Hui, Zhang Jun, et al. Modular microfluidics for life sciences[J]. *Journal of Nanobiotechnology*, 2023, 21(1):85.
- [22] Deng Chuanfu, Yang Shihao, Xie Rui, et al. Flexible fractal integration of microfluidic modules for controllable mass production of monodisperse microdroplets[J]. *Industrial & Engineering Chemistry Research*, 2023, 62(32):12690–12702.
- [23] Lai Xiaochen, Yang Mingpeng, Wu Hao, et al. Modular microfluidics: Current status and future prospects[J]. *Micro-machines*, 2022, 13(8):1363.
- [24] Han Tengfeng, Zhang Li, Xu Hong, et al. Factory-on-chip: Modularised microfluidic reactors for continuous mass production of functional materials[J]. *Chemical Engineering Journal*, 2017, 326:765–773.
- [25] Sugiura S, Nakajima M, Seki M. Prediction of droplet diameter for microchannel emulsification[J]. *Langmuir*, 2002, 18(10):3854–3859.
- [26] Li Z, Leshansky A M, Pismen L M, et al. Step-emulsification in a microfluidic device[J]. *Lab on a Chip*, 2015, 15(4):1023–1031.
- [27] Eggersdorfer M L, Seybold H, Ofner A, et al. Wetting controls of droplet formation in step emulsification[J]. *Proceedings of the National Academy of Sciences of the United States of America*, 2018, 115(38):9479–9484.
- [28] Ofner A, Moore D G, Rühls P A, et al. High-throughput step emulsification for the production of functional materials using a glass microfluidic device[J]. *Macromolecular Chemistry and Physics*, 2017, 218(2):1600472.
- [29] Dangla R, Kayi S C, Baroud C N. Droplet microfluidics driven by gradients of confinement[J]. *Proceedings of the National Academy of Sciences of the United States of America*, 2013, 110(3):853–858.
- [30] Su Yaoyao, Pan Dawei, Zhang Taoxian, et al. Wetting-induced interfacial instability: A mechanism for droplet emission at air-liquid interfaces[J]. *Science Advances*, 2025, 11(12):eads1065.
- [31] Link D R, Anna S L, Weitz D A, et al. Geometrically mediated breakup of drops in microfluidic devices[J]. *Physical Review Letters*, 2004, 92(5):054503.
- [32] Agnihotri S N, Raveshi M R, Nosrati R, et al. Droplet splitting in microfluidics: A review[J]. *Physics of Fluids*, 2025, 37(5):051304.
- [33] Vigogne M, Neuendorf T A, Bernhardt R, et al. Combining parallelized emulsion formation and sequential droplet splitting for large-scale polymer microgel production[J]. *Journal of Polymer Science*, 2023, 61(16):1902–1911.
- [34] Li Zida, Li Luoquan, Liao Meixiang, et al. Multiple splitting of droplets using multi-furcating microfluidic channels[J]. *Biomicrofluidics*, 2019, 13(2):024112.
- [35] Deng Chuanfu, Wang Wei, Xie Rui, et al. Recent progress in scale-up integration of microfluidic droplet generators[J]. *CIESC Journal*, 2021, 72(12):5965–5974. [邓传富, 汪伟, 谢锐, 等. 液滴微流控的集成化放大方法研究进展[J]. *化工学报*, 2021, 72(12):5965–5974.]
- [36] Schuler F, Schwemmer F, Trotter M, et al. Centrifugal step emulsification applied for absolute quantification of nucleic acids by digital droplet RPA[J]. *Lab on a Chip*, 2015, 15(13):2759–2766.
- [37] Schuler F, Paust N, Zengerle R, et al. Centrifugal step emulsification can produce water in oil emulsions with extremely high internal volume fractions[J]. *Micromachines*, 2015, 6(8):1180–1188.
- [38] Schulz M, von Stetten F, Zengerle R, et al. Centrifugal step emulsification: How buoyancy enables high generation

- rates of monodisperse droplets[J]. *Langmuir*, 2019, 35(30): 9809–9815.
- [39] Femmer T, Jans A, Eswein R, et al. High-throughput generation of emulsions and microgels in parallelized microfluidic drop-makers prepared by rapid prototyping[J]. *ACS Applied Materials & Interfaces*, 2015, 7(23): 12635–12638.
- [40] Mulunch M, Issadore D. Hybrid soft-lithography/laser machined microchips for the parallel generation of droplets[J]. *Lab on a Chip*, 2013, 13(24): 4750.
- [41] Kamperman T, Teixeira L M, Salehi S S, et al. Engineering 3D parallelized microfluidic droplet generators with equal flow profiles by computational fluid dynamics and stereolithographic printing[J]. *Lab on a Chip*, 2020, 20(3): 490–495.
- [42] Wu Jun, Kong Tiantian, Yeung K W K, et al. Fabrication and characterization of monodisperse PLGA-alginate core-shell microspheres with monodisperse size and homogeneous shells for controlled drug release[J]. *Acta Biomaterialia*, 2013, 9(7): 7410–7419.
- [43] Kaimainen M, Marze S, Järvenpää E, et al. Encapsulation of betalain into w/o/w double emulsion and release during *in vitro* intestinal lipid digestion[J]. *LWT—Food Science and Technology*, 2015, 60(2): 899–904.
- [44] Chen Li, Xiao Yao, Zhang Zhiming, et al. Porous ultrathin-shell microcapsules designed by microfluidics for selective permeation and stimuli-triggered release[J]. *Frontiers of Chemical Science and Engineering*, 2022, 16(11): 1643–1650.
- [45] Sheng Jianpeng, Wu Jiangchao, Yin Xianghong, et al. Synergistic treatment of oxygen microcapsules and lenvatinib for enhanced therapy of HCC by alleviating hypoxia condition and activating anti-tumor immunity[J]. *Chinese Chemical Letters*, 2023, 34(4): 107738.
- [46] Leister N, Karbstein H P. Evaluating the stability of double emulsions—A review of the measurement techniques for the systematic investigation of instability mechanisms[J]. *Colloids and Interfaces*, 2020, 4(1): 8.
- [47] Jiao J, Rhodes D G, Burgess D J. Multiple emulsion stability: Pressure balance and interfacial film strength[J]. *Journal of Colloid and Interface Science*, 2002, 250(2): 444–450.
- [48] Wu Jingyu, Hwang Y H, Yadavali S, et al. Micro-patterning wettability in very large scale microfluidic integrated chips for double emulsion generation[J]. *Advanced Functional Materials*, 2024, 34(3): 2309718.
- [49] Lai Yukai, Opalski A S, Garstecki P, et al. A double-step emulsification device for direct generation of double emulsions[J]. *Soft Matter*, 2022, 18(33): 6157–6166.
- [50] Ofner A, Mattich I, Hagander M, et al. Controlled massive encapsulation *via* tandem step emulsification in glass[J]. *Advanced Functional Materials*, 2019, 29(4): 1806821.
- [51] Liu Zhaomiao, Li Dezhi, Wang Xiang, et al. Breakup regimes of double emulsion droplets in a microfluidic Y-junction[J]. *Physics of Fluids*, 2021, 33(10): 102009.
- [52] Fan Linling, Wang Wei, Ju Xiaojie, et al. High-throughput generation of monodisperse double emulsions *via* controllable symmetric splitting in Y-shaped microchannels[J]. *Chemical Engineering Journal*, 2024, 498: 155727.
- [53] Savage T, Basha N, McDonough J, et al. Machine learning-assisted discovery of flow reactor designs[J]. *Nature Chemical Engineering*, 2024, 1(8): 522–531.
- [54] Yang Zhenyu, Jiang Zhongning, Lin Haisong, et al. CeyeHao: AI-driven microfluidic flow programming with hierarchically assembled obstacles and receptive field-augmented neural network[J]. *Science Advances*, 2025, 11(31): eadx2826.
- [55] Wang Jixiang, Wang Hongmei, Lai Huang, et al. A machine vision perspective on droplet-based microfluidics[J]. *Advanced Science*, 2025, 12(8): 2413146.
- [56] Shin J, Kang R, Hyun K, et al. Machine learning-enhanced optimization for high-throughput precision in cellular droplet bioprinting[J]. *Advanced Science*, 2025, 12(20): e2412831.

【校友简介】



褚良银, 四川大学化学工程学院教授、常务副校长。国家杰出青年科学基金获得者, 入选教育部重要人才计划、国家有突出贡献中青年专家、国家百千万人才工程、科学中国人年度人物、英国皇家化学会会士、中国化工学会会士、全球华人化工学者学会会士。长期从事化工学科传质与分离研究, 发明了传质与分离过程调控强化新技术, 技术成果推广应用至世界五大洲 70 多个国家和地区, 在国内外推广应用 10 万余台(套)。通过技术创新解决了行业发展中的关键难题, 推动了行业科技进步, 经济效益和社会效益显著, 为推动相关产业绿色化高端化高质量发展做出了重要贡献。迄今已在 *Nat. Chem. Eng.*、*Sci. Adv.*、*Acc. Chem. Res.*、*Adv. Mater.*、*Angew. Chem. Int. Ed.*、*PNAS* 等国内外高水平学术刊物上发表 SCI 收录论文 380 余篇, 出版专著 7 部, 已获授权专利 106 项(其中美、欧、日专利 17 项), 成果编入化工及相关领域 9 部手册和 5 部百科全书。以第一完成人获国家技术发明奖二等奖和 4 项省部级科技进步奖一等奖, 获何梁何利基金科技创新奖、全国创新争先奖、中国产学研合作创新奖、侯德榜化工科技成就奖。

Progress on High-throughput and Controllable Generation of Microdroplets with Microfluidics

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Abstract:

Significance Microdroplets attract significant attention in various fields, including process intensification, biomedicine, and functional material fabrication, because of their remarkable interfacial and unique scale effects, which significantly enhance mass and heat transfer, improve reaction efficiency, and enable new functionalities. Microfluidic technology precisely regulates multiphase flows within microscale channels, enabling the controllable generation of highly monodisperse microdroplets. However, conventional microfluidic device with a single droplet generation unit generally exhibit intrinsically low throughput, making it difficult to meet the requirements of large-scale industrial production. Therefore, developing a high-throughput and controllable generation strategy is urgently required to synergistically enhance droplet productivity while maintaining high monodispersity.

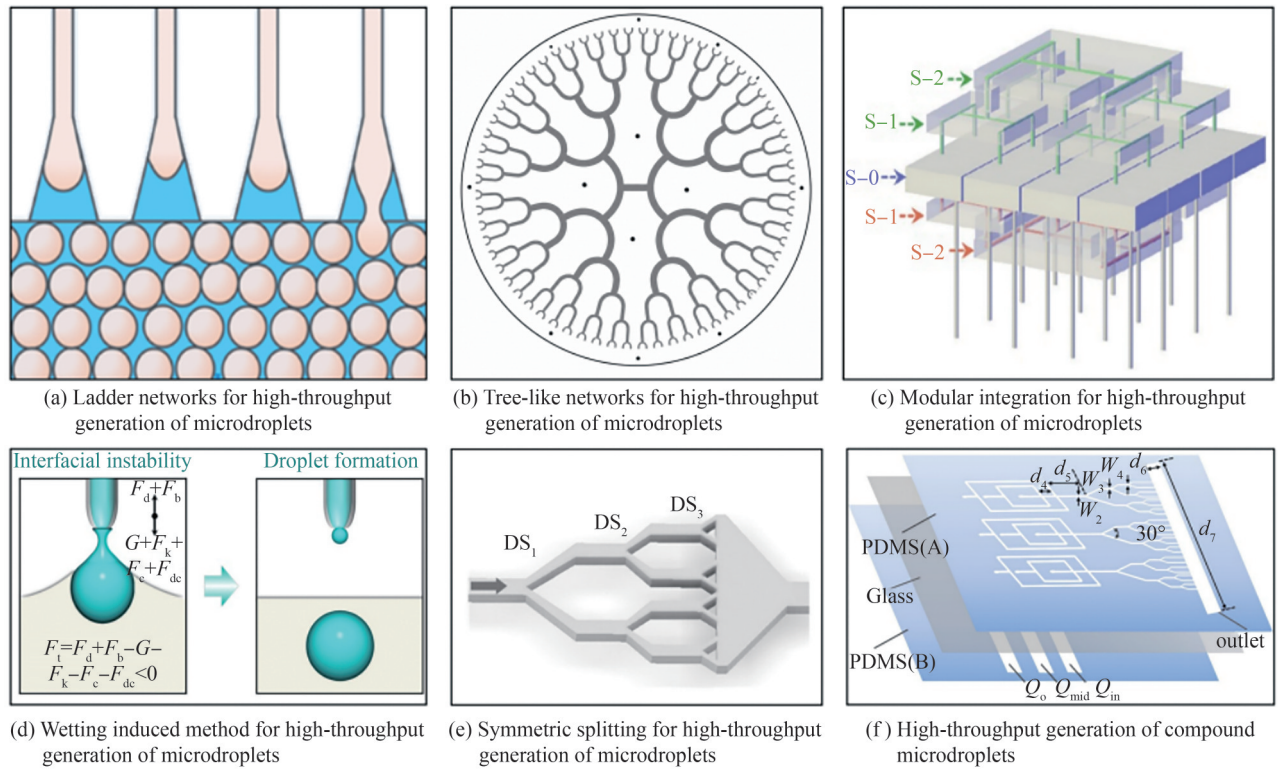
Progress Parallel scale-up strategies based on ladder networks, tree-like networks, and modular integration improved droplet production throughput by increasing the number of droplet generation units while enhancing droplet uniformity through the optimization of multiphase flow distribution networks. Among these strategies, ladder networks are characterized by high integration density, tree-like networks exhibit strong structural symmetry, and modular integration offer engineering advantages in terms of replaceability, configurability, and scalability, making parallelized microfluidic systems an important technical route for increasing droplet production capacity. However, such methods are still essentially flow-rate-coupled droplet generation modes. Their performance strongly depends on uniform flow distribution among multiple parallel channels. When the number of parallel channels is further increased, small differences in channel dimensions, hydraulic resistance, local pressure, and interfacial conditions are amplified across the network, resulting in nonuniform flow distribution and deterioration of droplet monodispersity. Therefore, flow-rate-decoupled scale-up strategies based on step emulsification and interfacial wetting-induced destabilization are further developed. In these methods, droplet formation is governed by interfacial tension, geometric confinement, and wetting behavior rather than by the shear force applied by the continuous phase. As a result, droplet size is primarily determined by the microchannel geometry or interfacial wetting characteristics and is relatively insensitive to the flow rate. This feature significantly reduces the requirement for highly uniform flow distribution under large-scale parallelized operation, overcoming the flow maldistribution commonly observed in conventional parallel microchannel networks. Step emulsification, for example, enables droplet breakup through the release of interfacial energy at a sudden geometric expansion, whereas interfacial wetting-induced destabilization utilizes local wettability differences to trigger controlled droplet formation. These flow-rate-decoupled mechanisms are therefore promising for robust and scalable droplet generation. However, their practical application is still limited by the ranges of compatible fluid systems, viscosities, and interfacial tension conditions, as well as by surface wettability requirements. Unlike strategies that increased the number of droplet generation units, symmetric splitting strategies achieve throughput amplification by inducing continuous droplet division under geometric confinement. In this approach, initially formed droplets are guided through designed microchannel structures and are split into smaller daughter droplets in a controlled and repeated manner, achieving multiplicative amplification of the droplet number. This strategy offers the advantages of a compact structure, high amplification efficiency, and reduced dependence on a large number of upstream droplet generation units. It provides a distinct route for high-throughput droplet production, particularly when the initial droplet generation process is stable and the downstream splitting geometry is precisely controlled. However, multistage continuous splitting also introduces new challenges. The stability of droplets during multistage splitting, the quantitative relationship between splitting geometry and droplet size, and the underlying interfacial stability mechanisms still requires further investigation. In addition to planar parallel scale-up and symmetric splitting strategies, three-dimensional (3D) microfluidic devices also provide an important technical platform for the high-throughput generation of microdroplets because of their high spatial integration density. Compared to planar microchannel systems, three-dimensional structures integrate droplet generation units in the vertical direction and incorporate more complex flow distribution networks within a limited chip footprint. These systems increase droplet production throughput per chip by employing centrifugal force, buoyancy-driven detachment, vertical stacking, and three-dimensional flow-guiding structures. In addition, parallel production and symmetric splitting strategies are utilized to improve the production throughput of compound microdroplets. However, compared to single-microdroplet systems, the generation of compound microdroplets involves the coupled evolution of multiple fluid interfaces and requires more precise control over surface wettability, flow distribution, and interfacial stability. Therefore, the high-throughput generation of compound microdroplets still face challenges related to uniform multiphase fluid distribution, stable encapsulation, interfacial compatibility, and operational reliability.

Conclusions and Prospects At present, high-throughput droplet microfluidic strategies enable efficient droplet production. However, the simultaneous improvement of droplet production throughput and monodispersity remains challenging. Future research should focus on improvements in

three aspects. First, physics-informed neural networks can be developed for the intelligent design of hydraulic resistance in complex microchannel networks. Specifically, physical constraints, such as mass conservation, pressure balance, and hydraulic resistance relationships in microchannels, can be embedded in neural networks and optimization algorithms. In this manner, an intelligent flow-resistance design model that integrates physical constraints with data-driven learning capabilities can be established. Through inverse optimization of structural parameters, including the number, length, width, and height of channels, as well as flow-resistance compensation structures, uniform flow distribution among parallel channels can be achieved. This approach is expected to reduce dependence on empirical design and repeated trial-and-error fabrication, improving droplet monodispersity and the operational stability of large-scale parallel droplet generation systems. Second, distributed multistage scale-up systems should be established by integrating flow-rate-decoupled step emulsification units with parallel production and symmetric splitting strategies, combining the robustness of flow-rate-decoupled droplet formation, the throughput advantages of parallelization, and the multiplicative amplification capability of symmetric splitting. This approach can simultaneously alleviate the challenges associated with excessive numbers of parallel channels and excessive splitting stages by distributing the scale-up burden across different levels. This integrated strategy is expected to overcome the limitations of a single scale-up mode and achieve the coordinated improvement of microdroplet throughput and monodispersity. Third, intelligent control platforms for high-throughput droplet generation should be constructed. An online sensing system for the droplet generation process can be established by integrating high-speed microscopic imaging, machine vision recognition, and real-time control algorithms. Key parameters, including droplet diameter, monodispersity, generation frequency, and the occurrence of abnormal droplets, can be monitored in real time. The recognition results can be fed back to the flow-rate control module to enable the adaptive adjustment of operating conditions. Through this closed-loop control strategy, high-throughput, continuous, and precise microdroplet generation can be achieved.

Key words: microdroplets; microfluidics;integrated scale-up; high-throughput generation; multiphase flow

Graphical abstract:



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