Table 1 Previous research on implemented R2R coating techniques, operating conditions, and products (D: dip coating, DG: direct gravure coating, K: knife-over-edge coating, MG: micro-gravure coating, SD: slot-die coating, LFS: liquid flame spray coating, S: spray coating)

Method	App.	Material	Solid contents	μ	V	h_0	f_r	Temp.	w	$t_{wet/dry}$
D[21]	DSSC	TiO_2	10wt%	-	1	-	-	120-140	-	10 (wet)
DG[22]	-	-	992-1088 kg/m^3	1-4	19.8-210	-	-	-	100	1-10 (dry)
K[28]	e-paper	TiO_2	-	-	9.14	-	-	179-192	-	12-40 (dry)
K[87]	OPV	ZnO	50 mg/ml	-	0.8	300	-	125-130	250	0.02 (dry)
K/MG[23]	Battery (Li)	Carbon	-	-	0.25-10	25 (K)	-	-	875-1185	2-200 (dry)
K/SD[31]	Fuel cell	PBI	9wt%	-	0.20	400	-	140	250	40 (dry)
LFS[24]	Paper (coated)	TiO_2	50 mg/ml	-	150	10^5-$25\cdot10^4$	23	75-110	50	1 (dry)
MG[32]	Sensor (flex)	Carbon	1120 kg/m^3	20	0.3 (web)	-	-	130	150	4.31 (dry)
MG[51]	TCF	PEDOT:PSS	-	1-1000	0.18	-	-	-	-	0.02 (dry)
SD[6]	AR	Si	1.5-5	3.3	1.6-4.4	100	2-13	140	100	0.06-0.13 (dry)
SD[73]	OPV	P3HT:PCBM	13.5 mg/ml	-	2	-	1.7	140	<305	0.129 (dry)
SD[88]	OPV	P3HT:PCBM/ PEDOT:PSS	60 mg/ml	25	240	-	-	140	-	100 (wet)
SD[33]	Sensor (piezo)	Ag	-	-	1.2-2.4	100	2-7	-	250	0.67-0.252 (dry)
SD[43]	PSA	PSA	20wt%	1800	2-10	100-400	10.65-53.74	120	150	4.5-5 (dry)
SD[74]	TCF	AgNW/ PEDOT:PSS	0.5wt%	-	2.7	100	3-25	150	260	-
SD[75]	TCF	PEDOT:PSS/ AgNW	10-20wt% (AgNW)	-	2-10	40-60	16.2-54	130	500	5-60 (wet)
SD[47]	TCF	CNT/AgNW/Si	-	2.12-8.68	1-2	30-50	3-9	110	250	1-26 (wet)
S[25]	SC	CNT	1 mg/ml	-	4 cm^2/s	-	-	-	-	4 (dry)

Units: μ (mPa·s), V (m/min), h_0 (μm), f_r (ml/min), Temp. (°C), w (mm), and $t_{wet/dry}$ (μm).

devices.[25] There have been many studies of spraying and evaporation of spray-coated layers.[67] Firstly, atomization is the key issue in spray coating, and can be expressed as in Eq. (11),[67]

$$W_e = \frac{\rho_g v^2 D}{\sigma_d} \tag{11}$$

By changing W_e, the breakup of drops for atomization is classified into three regimes: bagging, stripping, and catastrophic breakup.[85] From this equation, we can see that the liquid properties and gas flow can be determined for a uniform layer. This has been determined for uniform atomization. Nevertheless, there is no mathematical model of spray-coated thickness relating to the coating conditions in the R2R process. Moreover, the flight of droplets and their landing on the substrate with splashing must also be considered in obtaining a uniform layer.[86] However, LFS coating in the next section is worthy of notice because of its rapid and thick-layer coating ability.[24]

4. Roll-to-Roll Coating Applications

Research mentioned in this section shows R2R transportation performed for coating examples and applications. There have been many studies on various coatings that have the potential to be realized in R2R processes, but only the implemented cases were surveyed. In Table 1, the coating methods, applications, main coating materials, solid contents, viscosity, coating conditions such as V, h_0, f_r, and drying temperature, and coating output such as w and $t_{wet/dry}$ are summarized.

Slot-die coating was shown as the most used technique for R2R coating applications in the survey data listed in Table 1. OPV fabrication was actively researched using stripe coating of poly(3-hexylthiophene): phenyl-C61-butyric acid methyl ester [P3HT:PCBM] and poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) [PEDOT:PSS] on PET film coated by indium tin oxide (ITO).[73,88] The shim plate makes it possible to coat stripes. The fabricated module shows working IV curves, as shown in Fig. 6(a), which play a role in large-area modules as shown in the inset of Fig. 6(a). There has been research on anti-reflection (AR) coatings on PET films where Si material was used, indicating R2R compatibility.[6] Not only polymer material, but also Ag has been coated in R2R slot-die coating systems, forming a large-area conductive layer which was then patterned to ablate the unnecessary area by laser writing,[89] as shown in Fig. 6(b).[33] The fully coated and written Ag layer was used for piezoresistive sensors. Moreover, a PSA solution of high-viscosity liquid was fully coated on a PET substrate, as shown in Fig. 6(c). A PSA film product showed a uniformly coated layer that can be used in display and protective films.[43] Lastly, TCF was conducted many times[47,74,75] in previous works based on R2R slot-die coating. Fig. 6(d) shows one example of fully R2R-slot-die-coated silver nanowire (AgNW)/PEDOT:PSS hybrid film.[74] The inset of Fig. 6(d) shows a scanning electron microscope (SEM) image of a AgNWs network and PEDOT:PSS-covered surface that can enhance electrical properties. TCF has been widely adopted in electronics applications such as touch screens and OPVs.[3]

R2R gravure coating has been used for industrial applications, but has been more closely adapted to printing techniques.[36,77] In recent